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ABSTRACT

Designed for individualized use in an applied physics course in postsecondary vocational-technical education, this series of eighteen learning modules is equivalent to the content of two quarters of a five-credit hour class in manufacturing engineering technology, machine tool and design technology, welding technology, and industrial plastics technology. Almost all the modules contain technological application in the form of laboratory experiments or as applied homework problems. Each module contains the following components: a cover page explaining the purpose and contents of the module; learning objectives; learning activities; a self-evaluation test with an answer key; and a final test based on the stated objectives. These eighteen modules are a part of twenty-three applied physics modules which have been developed for use in several technology courses, including electrical, electronic service, electronic engineering, electromechanical, architectural and civil drafting, automotive, and diesel technologies. All twenty-three modules are available in ERIC document CE 014 409. Instructions in the use of the modules, related notes, data sheets, tests, and answer keys are included in a separate document (CE 014 408). (BM)

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ED150311

# Applied Physics Modules Selected for Manufacturing and Metal Technologies

October 1976

U S DEPARTMENT OF HEALTH.
EDUCATION & WELFARE
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CE 014 410

Southeast Community College--Milford Campus, Milford, Nebraska 68405

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 2

Title: Sizing Things Up

Module Contents:
1. Measuring systems
2. Fundamental and derived units
3. Conversion of units
4. The metric system
5. Precision measurement
6. Accuracy in measurement and computations

Program: This unit has been prepared especially for students in:
1. Mechanical manufacturing technology
2. Tool and design technology
3. Welding technology
4. Plastics technology

Purpose: The purpose of this module is to enable you to move forward in your chosen technology and in your physics course. The study of measurement, which is usually the first module of a physics course, is a prerequisite for most modules that follow in this couse. In order for your production (on the job) to meet necessary standards, the study of measuring systems, standards and conversion of units is an absolute requirement. With conversion to the metric system in the United States at an accelerated rate, it is necessary that you, as a manufacturing student, be familiar with and be able to use the metric system.

Producer: Gene Waring

Date Produced: August, 1976

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STUDENT INSTRUCTIONS

Module M 2 SIZING THINGS UP

## OBJECTIVES

When you have satisfactorily completed this module you will be able to:
1. Define fundamental and derived units.
2. Describe the standardization of fundamental units and give examples of at least five derived units.
3. Describe consistent measuring systems (British, mks and cgs) in terms of fundamental and derived units.
4. State the difference between an absolute and a gravitational measuring system.
5. Derive the units of a quantity, expressed in fundamental units (British, mks or cgs) when given the definition of the quantity.
6. State the conversion factors between commonly used units of time, distance, area, volume, and weight within the British measuring system.
7. State the name of, the abbreviation for, and the factor of the commonly used metric prefixes.
8. Convert a given quantity from one unit to another (British to British, metric to British, British to metric, or metric to metric) using the method of unit analysis, given a table of conversion factors.
9. State the definition of mass density and weight density.
10. State the formulas for the area and volume of commonly shaped objects (rectangles, circles and triangles - rectangular solid, cylinder and sphere).
11. Define the words: accuracy and uncertainty.
12. Round computed answers correctly to indicate the uncertainty in computations.
13. Estimate lengths and volumes of objects in metric units to at least 15%.
14. Use a balance to measure the weight or mass of various objects.
15. Use a vernier caliper to measure the length of an object to 0.1 mm or 0.01 in.
16. Use a micrometer caliper to measure the length of objects to within 0.01 mm and/or 0.001 in.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of measurement. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions, correctly. The answer key page (pink page 6 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 3 ).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject.

If the results of your self-evaluation test indicates your knowledge of measuring systems in general is weak, do the reading. If you have trouble converting units, practice solving problems. If the metric system or the use of measuring instruments is your weakness, do the experiments. You may want to do most or all of the activities if your overall background requires it. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook and the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper, (page 7). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N. C., Hemmerling, E. M., McGraw-Hill, 3rd ed., 1972. Read all of chapters 2, pages 23-28.

C. Elements of Physics, Smith, A. W., Cooper, J. N., McGraw-Hill, 8th ed., 1972. Read all of chapter 1, pages 2-12.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, l., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 1, pages 1-14.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read all of chapter 1, pages 1-11.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read section 1.8 in chapter 1, pages 14-16 and section 6.7 in chapter 5, pages 70-73.

II. Listening/Viewing: The following filmstrips with cassette tapes are available in the learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the projection and sound equipment (Hitachi SPR-771) and must precede the viewing of the films. Ask the LRC personnel about this training.

A. The International System of Units (SI), (QC/93/.U2x/1974). A four-part series.

1. CL-550-5 Introduction to the International System of Units
2. CL-550-7 Metric Units: Mass and its Derivatives

You need not view the two unlisted films in this series since they will be a part of other applied physics modules.

B. Understanding the Metric System, (QC/95/.I8x/1973). A four-part series.

1. C1-550-12 Measuring Volume

You need not view the three unlisted films in this series since they are introductory.

The following 35 mm film is available in the LRC. Ask the LRC personnel for a training session to familiarize you with the projector which must precede the viewing of the film.

A. The Outside Micrometer, (MP-46) L. S. Starrett Co., (1972)

III. Solving Problems: Solve the even numbered problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of the even numbered problems as you feel are necessary to gain competence in manipulating units.

IV. Solving Problems (Optional): Solve the odd numbered problems in the problem set in this booklet. These are for additional practice if you feel it is needed.

V. Performing Laboratory Experiments: There are five experiments in this module. They will give you practice in learning metric measurements of distance, volume, mass and density. One experiment will give you practice making distance measurements with precision instruments.

Read the laboratory instruction in this booklet (on yellow paper) and pay particular attention to the cautions given. Obtain a laboratory data sheet (M-2) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

## Module M 2 SIZING THINGS UP

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The three fundamental quantities adopted for mechanics in an absolute measuring system are time, mass, and distance.

T - F 2. The prefix meaning one thousandth is mega and its abbreviation is the capital letter M.

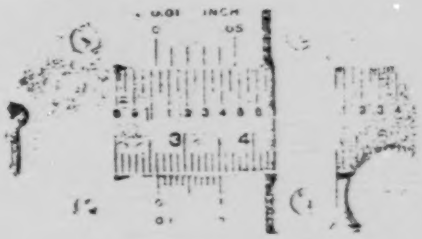
T - F 3. The term "uncertainty" generally refers to the reliability of measuring instruments.

T - F 4. A liter is about 6% larger than a quart.

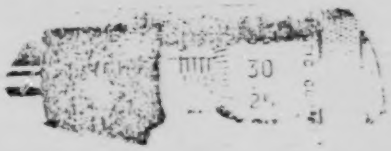
T - F 5. An equivalent of 110 mi/h is 75 ft/s.

6. The density of battery acid is 10.8 lb/gal. In grams per cubic centimeter it is
   a) 13.6 c) 1.3
   b) 8.33 d) 1.0

7. Density is defined as: density = mass/volume and volume = constant x $(\text{distance})^3$. The fundamental units of density in the mks measuring system is
   a) $m^3/kg$ c) $kg/m^3$
   b) $kg \cdot m^3$ d) $lb/ft^3$



8. The reading of the vernier caliper in millimeters is
   a) 2.61 c) 2.01
   b) 2.51 d) 3.50



9. The reading of the micrometer caliper in millimeters is
   a) 4.319 c) 3.819
   b) 4.819 d) 5.319

10. How many millifarads is 37.6 μF?
   a) 37 600 000 c) 37 600
   b) 0.0000375 d) 0.0375

11. Which of the following is the largest?
   a) 2 200 milliliters c) 0.25 cubic feet
   b) 15 pints d) 500 cubic inches

12. The speed of an electric wave in a transmission line is 130 000 mi/s. Express this speed in kilometers per hour.

## ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 2 SIZING THINGS UP

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. T | I Reading or II Listening/Viewing |
| 2. F | II Reading or II Listening/Viewing |
| 3. F | I Reading (Information Page) |
| 4. T | V Performing Laboratory Experiments |
| 5. F | III Solving Problems |
| 6. c | III Solving Problems |
| 7. c | III Solving Problems and I Reading (Information Pag |
| 8. a | V Performing Laboratory Experiments |
| 9. b | V Performing Laboratory Experiments |
| 10. d | III Solving Problems |
| 11. d | III Solving Problems |
| 12. $7.53 \times 10^8$ km/h | III Solving Problems |

INFORMATION SHEET

Module M 2

## SIZING THINGS UP

A consistant measuring system requires that a few quantities be defined independently of all others. These few quantities are called fundamental quantities. One of the units used to measure fundamental quantities is also defined in a fundamental way, i.e., independent of other units. Three fundamental quantities and their fundamental units are required in the study of mechanics. Additional fundamental quantities and their units are required in the study of heat, optics and electricity.

There are two types of measuring systems: absolute and gravitational. Both types use time and distance as fundamental. The difference being in the choice of the third quantity. An absolute system uses mass for the third quantity; a gravitational system uses weight. The mks (meter - kilogram - second) and the cgs (centimeter-gram-second) systems of measurement, using metric units, are both absolute systems. The British system is gravitational. See table 1 for the fundamental units of these three systems.

| System | Time | Distance | Mass | Weight (force) |
|---|---|---|---|---|
| Absolute mks | second | meter | kilogram | --------------- |
| cgs | second | centimeter | gram | --------------- |
| Gravitational British | second | foot | -------- | pound |

Table 1. Fundamental units of the common measuring systems.

WHY THE DIFFERENCE?

The weight of an object varies over the surface of the earth; from sea level to mountain top; from equator to poles, with local variations besides. Large variations in an object's weight occurs when it is moved to outer space. Weight depends on gravity. Thus, the choice of weight as fundamental gives rise to the name gravitational system.

The mass of an object, however, does not vary. It is the measure of the inertia of the object. The inertia depends only on the amount of matter the body contains; the number of protons, neutrons and electrons that make up the object. So the mass of an object is the same at sea level as on a mountain top and in outer space. Since mass is absolutely constant we have the name; absolute measuring system.

The concept of mass and the concept of weight are not difficult to distinguish. However, people tend to forget the difference. Actually, the confusion stems from the fact that both can be measured on the same measuring instrument. If you place equal weights on the pans of a balance scale, you have also placed equal masses on the pans. You should keep the statements of the two previous paragraphs in mind. The distinction between mass and weight will become clearer with further study of physics.

## FUNDAMENTAL UNITS

**Time:** All three systems described in table 1 uses the second as the fundamental unit of time. The second has an exact definition, (see your textbook). Other units of time are defined for particular uses in terms of the second; 1 minute = 60 seconds, 1 hour = 3600 seconds, etc.

**Distance:** The meter is the fundamental unit of distance in the mks system, (see your textbook for the precise definition). The unit of distance in the cgs and British systems are legally defined in terms of the meter; 1 centimeter = 0.01 meter, 1 foot = 0.3048 meters. Other units for particular purposes are defined in terms of the fundamental units; 1 yard = 3 feet, 1 kilometer = 1000 meters, etc.

**Mass:** The fundamental unit of mass in the mks system is the kilogram and in the cgs system, the gram. (See your textbook for the precise definition of the kilogram; 1 gram = 0.001 kilogram.) The slug is the unit of mass in the British gravitational system; (1 slug = 14.59 kilogram). Mass is not a fundamental unit in the British system, however, it is defined in terms of weight, time and distance within that system.

**Weight (Force):** In the British system, weight is fundamental. The unit is the pound, defined as the weight of 0.54359237 kilograms of mass. The newton (mks) and the dyne (cgs) are derived units of weight and are defined in terms of the units of mass, time, and distance in their respective measuring systems.

## DERIVED UNITS.

Units of derived quantities come from a definition of the quantity (usually a formula) and can be expressed as a combination of fundamental units in a given measuring system.

**Area:** Area is probably the simplest derived quantity. All the familiar formulas for area are of the form:

Area = Constant x distance x distance (1)

In some formulas such as the rectangle, the constant is 1 so it doesn't appear in the formula. In the area formula for a circle the distances are identical (radius). The constant has no units in area formulas, but the fundamental units (British) for distance is the foot. According to the formula, the derived unit for area is:

$$\text{feet} \times \text{feet} = \text{feet}^2$$

read feet squared or square feet. The units multiply together just as numbers do in arithmetic, e.g., $3 \times 3 = 3^2$; or as letters do in algebra, e.g., $a \times a = a^2$. You should get used to writing $ft^2$ for the units of area. It is easier to write than the words square feet or even the abbreviation ft sq. You should also remember that it means ft x ft.

**Volume:** The volume formulas for common solid objects have the form:

Volume = Constant x distance x distance x distance (2)

In the British system the derived units are therefore; feet x feet x feet $\text{feet}^3$. The derivation is similar to that for area.

**Velocity**: Formulas for velocity have the form:

$$\text{Velocity} = \frac{\text{distance}}{\text{time}} \qquad (3)$$

The derived units (British) are feet/second, read feet per second.

**Acceleration**: Acceleration is the rate of change of velocity:

$$\text{Acceleration} = \frac{\text{velocity}}{\text{time}} \qquad (4)$$

Its units, therefore, are feet/second/second = feet/second x 1/second = feet/sec x sec = $\text{ft/sec}^2$. Notice the units can be manipulated just as letters in algebra; to divide by a fraction, you invert the denominator and multiply. The units are read: feet per second squared or feet per second per second.

**Mass**: The mass of an object is given by the formula:

$$\text{Mass} = \frac{\text{weight}}{\text{acceleration}} \qquad (5)$$

Its British units are therefore: $\text{lb/ft/sec}^2$ or $\text{lb}\cdot\text{sec}^2\text{/ft}$, read pound second squared per foot. This complex combination of fundamental units is given the name slug for convenience.

**Weight**: Solving formula (5) for weight, it becomes:

$$\text{Weight} = \text{mass} \times \text{acceleration} \qquad (6)$$

Weight is fundamental in the British system but is derived in both absolute systems. The mks unit of weight is $\text{kg} \times \text{m/sec}^2 = \text{kg}\cdot\text{m/sec}^2$. This combination of units is called the newton. The cgs unit is $\text{g}\cdot\text{cm/sec}^2$ and is called the dyne.

## OTHER DERIVED UNITS.

Other quantities in mechanics have derived units, also. Some examples are: pressure, density, work, power and momentum. See problem sets for their definitions.

## OTHER FUNDAMENTAL UNITS.

When studying units of heat, a fourth fundamental unit is required. The unit is that of temperature and is the Celsius degree in the mks system. In physical optics, a fifth fundamental quantity (luminous intensity) has units of candela. In the study of electricity a sixth quantity (electric current) has the unit; ampere. These are all defined independently and, of course, precisely. All are mks units.

## ELECTRICAL DERIVED UNITS.

**Electric Charge**: The defining formula for electric charge is:

$$\text{Electric charge} = \text{current} \times \text{time} \qquad (7)$$

**Voltage**: Potential difference is defined by:

$$\text{Potential difference} = \frac{\text{work}}{\text{charge}} \qquad (8)$$

Resistance: Electrical resistance is defined by Ohm's law:

$$\text{Resistance} = \frac{\text{potential difference}}{\text{current}} \qquad (9)$$

The derivation of the units of charge, potential difference and resistan in terms of fundamental units is left as an exercise.

HINTS ON CONVERSION OF UNITS

1. If you wish to express a quantity in smaller sized units, you must hav a larger number of them to express the same quantity.
   Examples: 1. 3.5 ft = 42 in
   2. 25 volts = 25 000 mv
   3. $3 \times 10^{-4}$ amp = $3 \times 10^{-1}$ ma

   When you work strictly with metric units you must move the decimal to the right or increase the power of 10.

2. If you wish to express a quantity in larger units, you must have a smaller number of them to express the same quantity.
   Examples: 1. 150 min = 2.5 hr
   2. 3.54 w = .00354 kw
   3. $4 \times 10^{5}$ μa = $4 \times 10^{2}$ ma

   When you work strictly with metric units you must move the decimal to the left or reduce the power of 10.

3. The following tables list the correct symbols for prefixes and various quantities as established by the 1960 Conference of the International Bureau of Weights and Measures.

| Prefixes | Multiple | Symbol |
|---|---|---|
| terra | $10^{12}$ | T |
| giga | $10^{9}$ | G |
| mega | $10^{6}$ | M |
| kilo | $10^{3}$ | k |
| hecto | $10^{2}$ | h |
| deka | $10^{1}$ | da |
| deci | $10^{-1}$ | d |
| centi | $10^{-2}$ | c |
| milli | $10^{-3}$ | m |
| micro | $10^{-6}$ | μ |
| nano | $10^{-9}$ | n |
| pico | $10^{-12}$ | p |
| femto | $10^{-15}$ | f |
| atto | $10^{-18}$ | a |

Table 2. Symbols for prefixes

| Quantity | Base Unit | Symbol |
|---|---|---|
| length | meter | m |
| volume | liter | l |
| mass, force | gram, newton | g, N |
| time | second, hour | s, h |
| | minute | min |
| work-energy | joule | J |
| power | watt | W |
| current | ampere | A |
| potential | volt | V |
| resistance | ohm | Ω |
| inductance | henry | H |
| capacitance | farad | F |
| frequency | hertz | Hz |
| temperature | Celsius | C° |

Table 3. Symbols for quantities

The following diagram may be helpful in converting units (metric to metric).

If you are starting with a unit and going to a smaller one (moving downward in table 2), move the decimal to the right or increase the power of 10.

If you are starting with a unit and goint to a larger one (moving upward in table move the decimal to the left or reduce the power of 10.

Figure 1

4. Converting units that are not strictly metric is more difficult. Converting from British to British, British to metric or metric to British involves conversion factors that are not multiples of ten.

Conversion factors listed in tables are usually in the form:

1. 1 mi = 5280 ft
2. 1 $ft^2$ = 929 $cm^2$
3. 1 gal = 3.786 ℓ

The factor on either side can be taken to the other side by the usual mathematical rules (division rule). The ratio of two equal factors is numerically equal to 1 (one). For example:

1. 1 mi/5280 ft = 1
2. 1 ft /929 $cm^2$ = 1
3. 1 gal/3.786 ℓ = 1

Multiplication of a quantity by such ratios results in no change in the size of the quantity. A transformation of units is the only result. The following examples illustrate this and presents a method of converting that should leave no doubt in your mind about whether to multiply or divide by the conversion factor.

EXAMPLE: Convert 64.5 m to feet.

Solution: $$64.5\ \text{m}\left(\frac{3.281\ \text{ft}}{1\ \text{m}}\right) = 212\ \text{ft}$$

Notice that meters was placed in the denominator so it would cancel the meters in the given quantity, an equivalent solution:

$$64.5\ \text{m}\left(\frac{1\ \text{ft}}{0.3048\ \text{m}}\right) = 212\ \text{ft}$$

Any number in a numerator is a multiplier; any number in the denominator is a divisor.

EXAMPLE: Find the number of seconds in 3 weeks.

Solution: $$3\ \text{Wk}\left(\frac{7\ \text{da}}{1\ \text{wk}}\right)\left(\frac{24\ \text{h}}{1\ \text{da}}\right)\left(\frac{3600\ \text{s}}{1\ \text{h}}\right) = 1\ 810\ 000\ \text{s}$$

Notice the given quantity is multiplied by the number one, three times. Seconds is the only unit that didn't cancel so that's the units of the answer.

EXAMPLE: Convert 60 mi/h to feet per second.

Solution: $$60\ \text{mi/h}\left(\frac{5280\ \text{ft}}{1\ \text{mi}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right) = 88\ \text{ft/s}$$

Notice that hours is in the denominator of the given quantity so it is placed in the numerator of the second conversion ratio in order to cancel.

Always set up simple conversion problems on paper in the manner illustrated. In the long run you will save time and effort. Once the method is learned you will find yourself making few mistakes.

## ACCURACY AND UNCERTAINTY

Every industrial measurement involves error. However, many students are not familiar with the arithmetic of numbers that are not exact. Their mathematical training gave them little or no practice in finding the uncertainty in a product, for example, of two measurements, both of which are uncertain.

Accuracy: The term accuracy of a measurement, although it has various meanings, usually refers to the reliability of a measuring instrument. It is usually expressed by stating the uncertainty in the measurement. The diameter of a crankshaft journal, for example might be 2.125 ± 0.0005 in.

The true or accepted value lies somewhere between 2.1245 in and 2.1255 in. It is impossible to measure the exact value. However, the accuracy can be increased by using more refined measuring instruments.

Uncertainty: The uncertainties or errors in the measurement may be of two classes; erratic or systematic. A systematic error creeps into measure ments when measuring devices are not calibratd correctly. All the readings might be systematically too high or too low, for example. Systematic errors contrast with erratic or random errors as the following example indicates.

Hold a slender pointed object such as a ball point pen about an inch above the scale in figure 2 near the 1.5 mark (above the arrow). This arrangement might represent the scale and needle of a voltmeter. Hold your eye about 10 inches above the object and move your head back and forth. The needle appears to give different readings even through you are not moving it. No two people will place their eye in exactly the same place and hence there will be a number of different readings. These different readings are indicative of parallax errors which are of the erratic class.

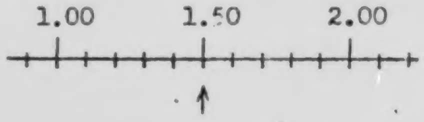


Figure 2

One person might record 1.52, another 1.50. Others might give readings of: 1.46, 1.48, 1.50, 1.48, 1.48, and 1.46. Perhaps when you took your reading, you thought it read 1.50. The mean or average value of the ten readings is: 1/10(1.52 + 1.50 + ...) = 1.49. The voltage, therefore, is 1.49 volts.

The true value, no doubt, lies somehwere between the highest reading (1.52) and the lowest (1.46). We could then represent the reading as 1.49 ± 0.03. However, the uncertainty is probably not as great as 0.03. It will normall not be greater than the average deviation from the mean value. The deviation from the mean is 1/10(0.03 + 0.01 + ...) = 0.017 or approximately 0.02. This would indicate a reading of 1.49 ± 0.02. This value is probably the best value of the voltage we could give from the data taken in the example.

Sometimes the percentage error is given instead of the actual error. This can be found by dividing the actual error (0.02) by the mean value (1.49) and multiplying by 100. The voltage is 1.49 ± 1.34% which is identical t 1.49 ± 0.02.

## AN EASIER WAY

When using real measuring instruments, the uncertainties are normally not as large as indicated by the above example. Most measurements are made to an açcuracy between 0.1% and 1%. Some of the readings, if they are bad enough, are called blunders and may be dropped from the data.

If the error in the reading, in the example above, was no more than 0.005, we could simply write the mean value as 1.49. When the actual or percentage error is not given, we would assume the true reading lies somewhere between 1.485 and 1.495, in the example. Note that this indicates greater accuracy than 1.49 ± 0.02.

From this point on, we will assume that our measuring instruments are accurate enough to write the numbers in the simplified form.

## SIGNIFICANT FIGURES

In the measurement in the example above (1.49), it appears that the first two figures (the one and the four) are quite certain even though not everyone agreed the second figure was a four. Its certainty is derived from the mean value. The third figure (nine) is not so certain. As a matter of fact not one of the ten people recorded it as a nine. The figures that are certain and the first really doubtful one are called significant figures. Thus, the one, the four, and the nine are significant.

## CALCULATIONS USING MEASURED VALUES

When you use measured values in calculations, the product or quotient will sometimes end up with many more figures than any of the factors involved.

RULE: Calculated answers of products or quotients should be rounded off so the answer has no more significant figures than the factor that has the least number of significant figures.

Example: Find the area of a circle whose radius is 1.12 in.

$$A = \pi r^2 = 3.1416 \times 1.12 \text{ in} \times 1.12 \text{ in} = 3.94093504 \text{ in}^2$$

The answer indicates an accuracy to the nearest 1/100,000,000 $\text{in}^2$. However, the radius was only measured to the nearest 1/100 in. Surely, we cannot know the area as accurately as this. The theory of errors or the simplified rule stated above would indicate that we should round off the answer to three significant figures since the radius was measured to three. So the area is 3.94 $\text{in}^2$. We can use $\pi = 3.14$ for most calculations.

If you use a slide rule, it will automatically round off the answers to three significant figures. However, if you use an electronic calculator, you will have to do the rounding off as an important part of solving problems.

PROBLEMS

Module M 2

## SIZING THINGS UP

1. Work out the units of area, volume, velocity, acceleration and weight; express each in fundamental mks units. The defining formulas are given in the information sheet in this booklet.

2. Work out the units of pressure, density, work, power and momentum; express each in fundamental mks units. The defining formulas are:

   a) pressure = $\frac{\text{force}}{\text{area}}$

   b) density = $\frac{\text{weight}}{\text{volume}}$

   c) Work = force x distance

   d) power = $\frac{\text{work}}{\text{time}}$

   e) momentum = mass x velocity

3. Work out the electrical units of potential difference, resistance and electric charge; express each in fundamental mks units. The defining formulas are given in the information sheet in this booklet.

4. Convert the following as indicated:
   a) 235 V to millivolts
   b) 764 mA to amperes
   c) 6.39 kW to milliwatts
   d) 7.5 km to decimeters

5. Convert the following as indicated:
   a) 30 ml to liters
   b) 40 hm to decimeters
   c) .00435 MV to microvolts
   d) 7 380 000 cm to kilometers

6. Convert the following as indicated:
   a) 440 yd to inches
   b) 50 000 oz to tons
   c) 14.7 lb/in$^2$ to pounds per square foot
   d) 80 mi/h to feet per second

7. A lathe has a 16 in swing with a 54 in center to center distance. Can a piece of stock with a radius of 19 cm and a length of 130 cm be turned in this lathe?

8. The length of rollers for certain roller bearings may range from 1.788 to 1.803 in as specified by the manufacturers. Express this range in millimeters.

9. What is the diameter of a 0.002 oversize, 1/2 inch reamer expressed in millimeters.

10. An electric motor that drives a press drill runs without a load at 1750 rpm. It makes one revolution every 0.0005714 min. Express this time in decimal form in seconds and in milliseconds.

11. A machine operator spent 7000 sec on a certain job. How many hours is this?

12. A lathe has a total mass of 1500 kg. What is its weight in pounds.

13. Five gallons of lubricant used in grinding has a weight of 35.5 lbs. What is the mass of five gallons of this lubricant in grams?

14. An electric motor on a large machine has a mass of 48 kg. What is its weight in newtons? In pounds?

15. A shipment of metal weighed 240 ton. What is its mass in kilograms?

16. A standard oxygen tank has an inside volume of 1.62 $ft^3$. How many liters is this?

17. How many liters are there in a 55 gal oil drum?

18. Sheet metal is cut into standard sheets 4 ft x 8 ft. Find the area of one side of one of these sheets in square meters.

19. A standard oxygen tank has several cubic meters of oxygen compressed into it. Compare the cubic yard and the cubic meter by calculating the number of cubic feet in each. The cubic yard is what percent of a cubic meter?

20. The small engine driving the generator of a portable electric welder will operate for 0.85 h/gal of gasoline. Convert this rate to seconds of operation per milliliters of gasoline.

21. A hydraulic pump causes oil to flow at a rate of 275 gal/h at high pressure. Express this rate in liters per minute.

22. A foreign advertisement states that their product (a car) gets 12 km/l of gasoline. What is this rate in miles per gallon.

23. A certain brand of welding rod sells for 0.48 $/lb. What would the cost be in dollars per kilogram at the same rate?

24. Liquid grinding coolant costs 119 ¢/l. What would the cost be for a 20 gal drum at the same rate?

25. The surface speed of a grinding wheel one foot in diameter is 100 ft/s What is this speed in miles per hour? In meters per second?

26. The density of the oil in problem 21 is 0.860 kg/l. Find the weight in pounds that is circulated by the pump in one minute.

27. The liquid grinding coolant in problem 24 has a density of 1.24 $g/cm^3$. What does a 20 gal drum weigh in pounds?

28. At normal atmospheric pressure, oxygen has a density of 0.00143 $g/cm^3$. What is the weight in pounds of the oxygen in a full tank if 144 $ft^3$ are compressed into it?

29. The following readings were made by a group of 11 people: 3.71, 3.68, 3.74, 3.74, 3.75, 3.71, 2.16, 3.70, 3.73, 3.69, 3.72. What is the mea value? Hint: remember that blunders may be dropped. What is the average deviation from the mean? Express the average deviation as a percentage.

30. The following readings were made by a group of 11 people: 5.14, 5.17, 5.19, 5.12, 5.08, 5.21, 5.84, 5.12, 5.19, 5.16, 5.13. Answer the same questions as stated in problem 29.

ANSWER KEYS (PROBLEMS)

Module M 2 **SIZING THINGS UP**

1. $m^2$, $m^3$, m/s, $m/s^2$, $kg \cdot m/s^2$
2. $kg/s^2 \cdot m$, $kg/s^2 \cdot m^2$, $kg \cdot m^2/s^2$, $kg \cdot m^2/s^3$, $kg \cdot m/s$
3. $kg \cdot m^2/s^3 \cdot A$, $kg \cdot m^2/s^3 \cdot A^2$, $A \cdot s$
4. $2.35 \times 10^5$, 0.764, $6.39 \times 10^6$, $7.5 \times 10^4$
5. 0.030, $4 \times 10^4$, $4.35 \times 10^9$, 73.8
6. 15 800, 1.56, 2 120, 117
7. 15.0 swing, 51.2 length, yes
8. 7.04 - 7.10
9. 1.98
10. 0.03428, 34.28
11. 1.94
12. 3310
13. 16, 100
14. 471, 106
15. 218 000
16. 45.9
17. 208
18. 2.97
19. 27 $ft^3$ - 35.3 $ft^3$, 76.5%
20. 0.81
21. 17.3
22. 28.2
23. 1.06
24. 90.09
25. 68.2, 30.48
26. 32.8
27. 207
28. 12.8
29. 3.72, 0.02, 0.54%
30. 5.15, 0.03, 0.58%

## EXPERIMENTS

### Module M 2

### SIZING THINGS UP

PURPOSE: The purpose of these experiments is to study some measuring instruments and methods of precision measurement; to practice estimating distances, mass and volume in metric units; and to compute area, volume and density of various commonly shaped objects.

CAUTIONS:

1. Read all of the instructions before handling any of the equipment.
2. The micrometer and vernier calipers, the Harvard trip balances and the brass weights are all precision instruments. Handle them with care.
3. Keep the plastic foam keeper in place on the Harvard trip balances when they are not in use.
4. Instead of taking the balances to your table to weigh objects, take the objects to the balance for weighing. Balances receive much less wear and tear this way.
5. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
6. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: The equipment for each experiment is listed in the procedure section. Check to see if it is all available before you start. Ask your instructor if you have questions about the equipment.

PROCEDURE: Experiment A "Linear Measurement"

Equipment:
1. One 15 cm plastic rule
2. Meter stick
3. Metric tape (10 m)
4. Box A (Objects listed on data sheet)

Estimate the thickness, width, height, etc., for each object listed on the data sheet. Then measure using a 15 cm rule or a meter stick. In the error column, write the difference between the estimated and measured values. Insert a + sign if your estimate is too large and a - sign if it is too small.

Complete one line at a time. Do not make all the estimates before doing any measuring. You should see improvement in your estimates as you proceed one line at a time. Estimate distances to the nearest centimeter in lines 1 through 11. Estimate lines 12 and 15 to the nearest meter. Calculate the areas in line 16 through 18.

Experiment B "Precision Measurement"

Equipment:
1. Sargent-Welch Measurement set #0056

Instructions for reading the micrometer and vernier calipers are given on the information sheet page 19. Practice using both of these instruments as indicated on the data sheet (lines 1 through 10). Calculate the volume of the sphere, small cylinder and the block (lines 11 through 13). Use the micrometer caliper measurements for volume calculations and retain only as many significant digits as is justified.

## Experiment C "Volume Measurement"

Equipment: 1. Various bottles listed on the lab sheet (Box C)
2. Various calibrated beakers and Pharmaceutical graduates.

Obtain a 1 to 2 liter beaker and fill it 3/4 full of water. Estimate the volume capacity (level full) of each spoon or bottle listed on the data sheet to the nearest milliliter. Measure each by filling with water. Use a small beaker to pour the water into them.

Pour the water from the bottles into one of the calibrated beakers or pharmaceutical graduates. Measure each as accurately as possible.

CAUTION: Use care not to spill water. Clean up with paper towels. Be careful! You are working with glass.

Complete one line on the data sheet at a time. Do not make all the estimates before measuring. You should see improvement in your estimates as you proceed one line at a time.

In the error column, write the difference between the estimated and measure volumes. Write a + sign if the estimate is too large and a - sign if it is too small.

## Experiment D "Mass Measurement"

Equipment: 1. Harvard trip balance (metric)
2. Box D. Various objects listed on lab sheet D.

Use the dynamic method of balancing (see information sheet page 19) to find the mass of each object listed on the lab sheet. Measure each object to the nearest 0.1 grams.

CAUTION: The maximum capacity is 1500 grams or 4 pounds. Do not overload

Calculate your mass in kilograms (line 9) and then measure it on the metri bathroom scale.

## Experiment E "Density"

Equipment: 1. Vernier caliper
2. Harvard trip balance
3. One object in box E

Use a vernier caliper to measure the dimensions of one of the blocks in box E. (How to use the vernier caliper is described in the information sheet, page 19.) Measure the height along each of the four sides and calculate the average. Record all data. Record four measurements of the length and width and the average of each. Make your measurements to the nearest 0.01 mm.

Using the average values of length, width and height, calculate the volume of the block (line 4).

Measure the mass of the block to the nearest 0.1 gram using the dynamic method (see information sheet, page 19). (Line 4.)

Calculate the density using measured values of mass and volume. (Line 6.)

| Substance | Density kg/m$^3$ | lb/ft$^3$ |
|---|---|---|
| Aluminum | 2,650 | 164 |
| Brass | 8,600 | 535 |
| Iron | 7,800 | 480 |

Table 4.

Compare calculations of density with that in Table 4 by calculating the percentage error.

$$\% \text{ error} = \frac{\text{difference}}{\text{standard value}} \times 100$$

INFORMATION: The following information about the micrometer caliper, the vernier caliper and the balance scale are included here for your convenience.

Use of the Harvard Trip Balance.

The Harvard trip balance uses a method of weighing by direct comparison with standard weights. The single beam balance is sensitive to 0.1 gram and the beam is graduated for 10 grams. The double beam balance (Figure 6) permits weighing up to 210 grams without added weights. The lower scale reads to 10 grams in 0.1 gram divisions. The upper scale reads to 200 grams in 10 gram divisions. The British balance back beam reads to 8 oz in 1 oz divisions while the front beam reads to 1 oz in either 0.01 oz or 1/64 oz divisions.

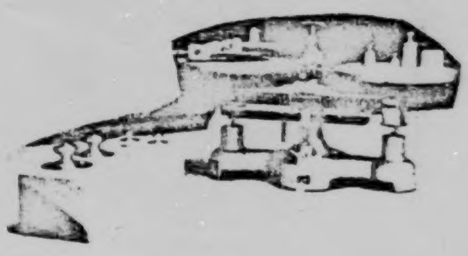


Figure 6.

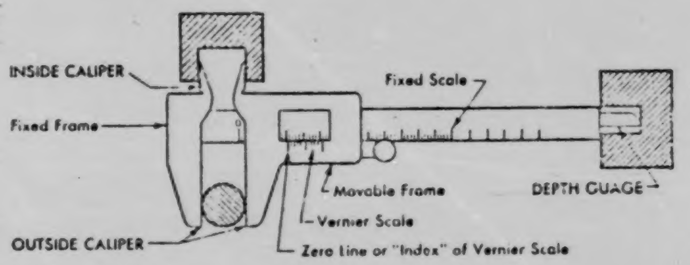
CAUTION: Maximum recommended capacity is 1500 grams or 4 lb.

Do not attempt to balance the scale with the pointer stopped on the center mark. Use a dynamic method of weighing; with the pans in motion, the pointer should swing the same amount on each side of the center mark. This method eliminates the slight amount of internal friction of the balance. Place the object to be weighed on the left pan; the standard weights on the right. Adjust slider on the balance beam to correct position for dynamic balance.

Use of the Vernier Caliper.

> "By permission from Sargent-Welch Scientific Company, Instructions for the use of Measurement Set Cat. No. 0056"

Measurements are made by sliding the movable frame along the fixed scale so that either the inside or outside caliper or the depth gauge covers the distance to be measured. See Figure 1. The caliper or depth indicator should fit snugly against the object to



be measured. Use the knurled thumb nut for this adjustment. Once the cal per or depth indicator is firm against the object to be measured, read the graduation on the fixed scale nearest the zero mark on the vernier scale. If the zero mark does not coincide with a fixed-scale graduation add the appropriate distance as read from the vernier scale.

Some examples in reading a vernier scale follow:

In Figure 2a, the distance is read as follows;

1. First read the fixed scale. Note that the zero line of the moveable scale does not coincide with a division on the fixed scale. Read the division on the fixed scale just to the left of the zero line. This reading is 3.70.

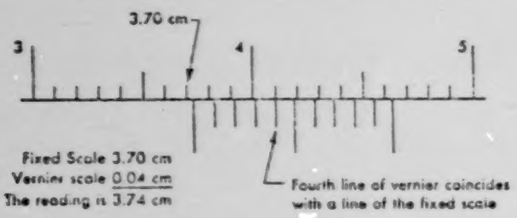

3.70 cm
3
4
5
Fixed Scale 3.70 cm
Vernier scale 0.04 cm
The reading is 3.74 cm
Fourth line of vernier coincides with a line of the fixed scale

Figure 2a

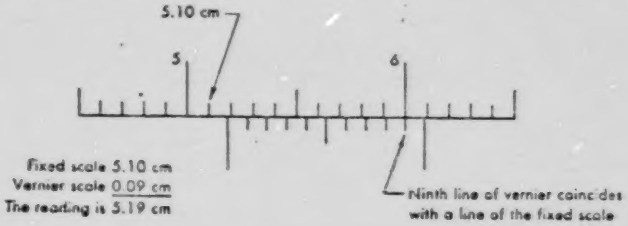

5.10 cm
5
6
Fixed scale 5.10 cm
Vernier scale 0.09 cm
The reading is 5.19 cm
Ninth line of vernier coincides with a line of the fixed scale

Figure 2b

2. The distance from the division just to the left of the zero line to the zero line is determined as follows. Starting from the zero line and moving to the right, count the lines on the vernier scale until a line is reached which most nearly coincides with a division on the fixed scale. In the example, this number is four.
3. Add 3.70 cm and 0.04 cm to get 3.74 cm.

The same procedure applies to reading the vernier on the British scale, but with each division on the vernier representing 1/100 of an inch.

Use of the Micrometer Caliper.

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The micrometer caliper in the measurement set has a pitch of 0.5 mm. This means that the screw advances 0.5 mm when turned through one revolution. Fractional revolutions of the screw are indicated by the graduations on the circumference of the thimble. See Figure 3. The scale around the circumference of the thimble is divided into 50 parts. Each division represents 1/50 of a revolution. When the thimble is turned through one division, the screw advances 1/50 of the pitch, i.e., 1/50 of 0.5 mm, or 0.01 mm.

Example: In Figure 4a, the thimble has been rotated through a fraction more than sixteen revolutions from zero. This corresponds to a distance of 8.00 mm, i.e., 16 rev x 0.500 mm/rev = 8.00 mm. The fractional revolution is 0.110 mm plus the length represented by the distance from the eleventh

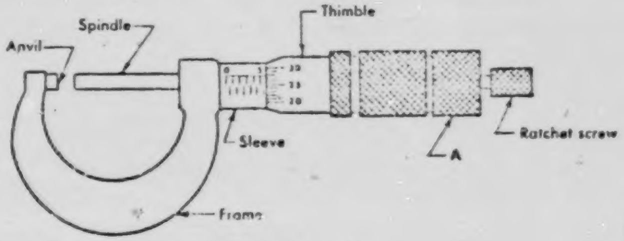
Thimble
Spindle
Anvil
0
5
20
15
10
Sleeve
A
Ratchet screw
Frame

Figure 3.

sleeve graduation to the spindle reference line. The reference line is approximately one-half of the way between the 11th and 12th sleeve graduation. Since these graduations represent 0.01 mm of measured distance, this fraction may be estimated as 0.005 mm.

Caution: Use the ratchet screw to avoid tightening the jaws so much that the frame will be strained. Always store the micrometer caliper with the jaws open. If the jaws are closed and the temperature increases, the frame may warp.

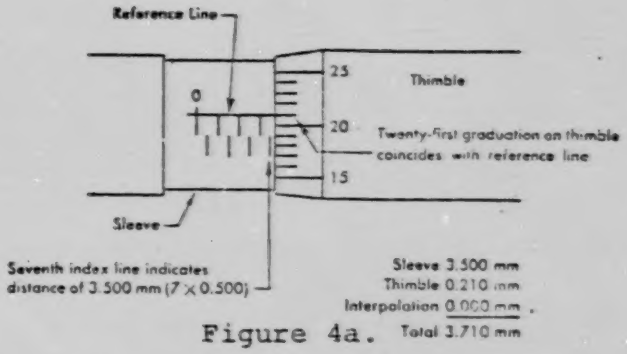
Reference Line
0
25
20
15
Thimble
Twenty-first graduation on thimble coincides with reference line
Sleeve
Seventh index line indicates distance of 3.500 mm (7 × 0.500)
Sleeve 3.500 mm
Thimble 0.210 mm
Interpolation 0.000 mm
Total 3.710 mm

Figure 4a.

Additional examples are given in figures 4b and 4c.

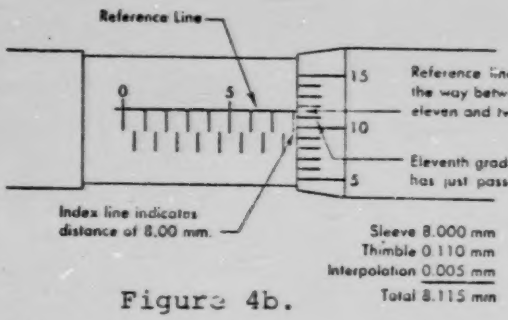
Reference Line
0
5
15
10
5
Reference line is one-half of the way between graduations eleven and twelve
Eleventh graduation on thimble has just passed reference line
Index line indicates distance of 8.00 mm.
Sleeve 8.000 mm
Thimble 0.110 mm
Interpolation 0.005 mm
Total 8.115 mm

Figure 4b.

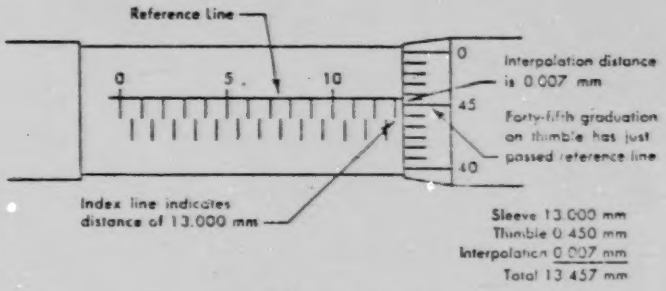
Reference Line
0
5
10
0
45
40
Interpolation distance is 0.007 mm
Forty-fifth graduation on thimble has just passed reference line
Index line indicates distance of 13.000 mm
Sleeve 13.000 mm
Thimble 0.450 mm
Interpolation 0.007 mm
Total 13.457 mm

Figure 4c.

Use of the Rule.

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There are a number of acceptable methods for use of the rule in measuring a given dimension of an object. One suggested method is to lay the rule across a flat portion of the object to be measured as shown in Figure 5.

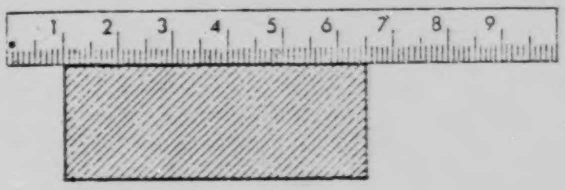

Figure 5.

Some graduation such as the 1-cm mark is lined up exactly with the left edge, and the reading of the rule at the right edge is made and recorded. The dimension of the object is obtained by subtracting the reading of the rule at the left edge (1.00 cm) from the reading at the right edge.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 3

Title: The Nature of Vectors

Module Contents:
1. Vectors
2. Composition of vectors
3. Resolution of vectors
4. Displacement
5. Equilibrium of concurrent forces

Program: This unit has been prepared especially for students in:
1. Manufacturing engineering technology
2. Machine tool and design technology
3. Welding technology
4. Industrial plastics technology
5. Electromechanical technology

Purpose: Forces, displacement, velocity, acceleration and other vectors have a direction associated with them. Balancing forces and torques and other applications require a thorough knowledge of the addition and resolution of vectors. Practical applications involving forces on bearings, welded joints, toggle joints, tools, etc. are included in the problem sets. This module is a prerequisite for others that follow.

Producer: Gene Waring

Date Produced: August 1976

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STUDENT INSTRUCTIONS

Module M 3 THE NATURE OF VECTORS

OBJECTIVES

When you have satisfactorily complete this module, you will be able to:

1. Define the following words and terms: vector, scalar, magnitude, line of action, point of application, concurrent forces, equilibrium, resultant, equilibrant, vector component, vector composition, and vector resolution.
2. Represent a vector quantity (both magnitude and direction) by an arrow.
3. Construct space (free body) diagrams.
4. Construct freehand vector diagrams and estimate the vector sum or difference (magnitude and direction) using the parallelogram or polygon methods.
5. Resolve a vector into its rectangular components given the magnitude and direction (Polar form).
6. Find the magnitude and direction (Polar form) of a vector given its rectangular components.
7. Find the vector sum or difference of vectors by the component method.
8. Apply the methods of vector addition to various practical problems involving displacement and concurrent forces.
9. Solve practical problems involving the equilibrium of objects under the influence of a set of concurrent forces.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of vectors. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink, page 6 ) directs you to various learning activities.

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4 ).

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read part of chapter 5, pages 113-121, and 125-128. (Omit sections 5-9 and 5-11)

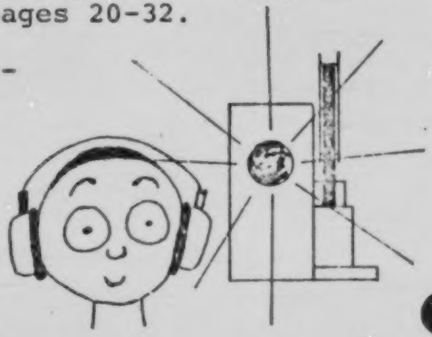
B. Elements of Physics, Smith A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read all of chapter 2, pages 16-23.

C. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapters 7 and 8, pages 70-100.

D. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read part of chapter 2, pages 12-20. (Omit sections 2-4)

E. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc. 1st ed., 1966. Read all of chapter 2, pages 20-32.

II. Listening/Viewing: The following single-concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film-loop projector (Technicolor) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. The Velocity Vector, (BFA Ealing 80-251) QC/231/V49x/#6

B. Vector Addition-Velocity of a boat, (BFA Ealing 80-3478)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page 10). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in manipulating vectors. Most of the problems from number six on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about vector addition of concurrent forces.

Read the laboratory instruction in this booklet on yellow paper and pay particular attention to the cautions given. Obtain a laboratory data sheet (M-3) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

## Module M 3 THE NATURE OF VECTORS

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page. DO NOT WRITE ON THIS TEST!

T - F 1. A vector is a quantity that is represented by a number, unit, and a direction.

T - F 2. A force of 25 lb makes an angle of 35° with the x-axis, its component in the y-direction is 14.3 lb.

T - F 3. Vector diagrams need not be drawn to accurate scale for the resultant to be shown correctly.

T - F 4. Displacements of 5, 9, 22, and 38 miles would allow an automobile to return to its starting point if the directions happen to be in a correct combination.

T - F 5. The process of separating vectors into their rectangular components is called vector resolution.

6. A force of 90 N makes an angle of 25° with the x-axis. Its horizontal component in newtons is:

a) 81.6 c) 38.0
b) 99.3 d) 213

7. Displacements of 15 km and 5 km, if the directions were correct, could be added to give a resultant magnitude in kilometers of:

a) 0 c) 17
b) 22 d) 4

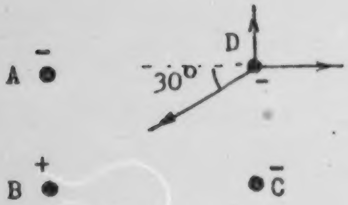
8. A force of 8 N acts perpendicular to a force of 11 N. The resultant has a magnitude in newtons of:

a) 19 c) 3
b) 13.6 d) 185

9. An automobile travels 6 miles north and then 6 miles in a direction 30° east of north. The magnitude of the resulting displacement in miles is:

a) 12.0 c) 9.00
b) 11.6 d) 36.0

10. Four electric charges are located at the vertices of a rectangle as shown in the diagram. Each charge exerts a force on each of the others. The forces on charge D are $F_A$ = 7 dynes, $F_B$ = 10 dynes, and $F_C$ = 15 dynes, with directions shown on the diagram. Find the resultant (magnitude and direction) of the forces on charge D.



11. Construct a careful freehand vector parallelogram on graph paper. Plot the following pair of forces: 28.2 N at 256°, and 37.1 N at 329°. Both angles are measured from the positive x-axis. Draw in the resultant and estimate its magnitude and direction.

ANSWER KEY TO THE SELF EVALUATION TEST

Module M 3 THE NATURE OF VECTORS

| Question-Answer Question-Answer | If you missed this question, you are directed to these learning activities: |
|---|---|
| 1. T | I. Reading or II. Listening/Viewing |
| 2. T | III. Solving Problems |
| 3. F | I. Reading or V. Performing Laboratory Experiments |
| 4. F | III. Solving Problems |
| 5. T | I. Reading or II. Listening/Viewing |
| 6. a | III. Solving Problems |
| 7. c | III. Solving Problems |
| 8. b | III. Solving Problems |
| 9. b | III. Solving Problems |

ANSWER KEY CONTINUED

Module M 3 THE NATURE OF VECTORS

| | | | |
|---|---|---|---|
| 10. | 10.1 dynes at 99.4° from the x-axis | V. | Performing Laboratory Experiments |
| 11. | $52.8\underline{/-61.8}$ | III.<br>V. | Solving Problems or<br>Performing Laboratory Experiments |

(Your estimate should be reasonable close)

PROBLEMS

Module M 3 THE NATURE OF VECTORS

1. What is the relationship between the resultant and the equilibrant of two or more forces?

2. Can the resultant of two unequal displacements be zero? Explain:

3. Can the resultant of three unequal displacements be zero? Explain:

4. Can either of two rectangular components of a displacement be larger than the displacement itself? Explain:

5. Does the odometer on a car measure a vector or scalar quantity? What quantity does it measure?

6. Two concurrent forces of 100 N and 75 N act on a body. What are the maximum and minimum possible magnitudes of the resultant force?

7. Find the east-west and north-south components of the force caused by the wind on a welded structure if the wind is blowing in a direction toward 30° south of east. The magnitude is 2856 lb.

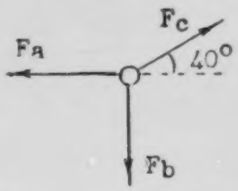
8. Find the horizontal and vertical components of the tension of 345 lb (total) on a motor exerted by v-belts pulling in a direction 40° with the horizontal.

9. Which of the following can be represented by a vector: (a) side force on a bearing due to v-belt tension, (b) the wind, (c) the motion of a lathe advance mechanism, (d) the mass of of Brinnel hardness testing machine, (e) the direction: 30° east of north, (f) the heat energy produced by cutting action of a lathe, (g) the force of gravity.

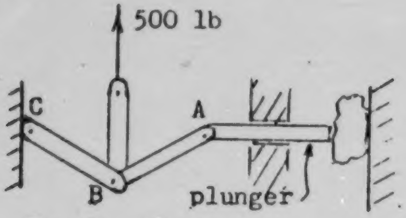
10. A mobile welding unit is located 8.2 miles, 25° south of west from the maintenance shop. How far south and how far west is he from the shop?

11. A three-jawed chuck used on a lathe to hold the stock being machined exerts a force of 215 lb on the stock by each jaw. If the jaws each have an angle of 120° between them, what is the resultant force on the machine stock?

12. A part of a bridge structure has forces on it with directions shown in the diagram. If $F_A$ = 3280 lb, $F_B$ = 4560 lb, and $F_C$ = 7120 lb; find the net force on the structure.



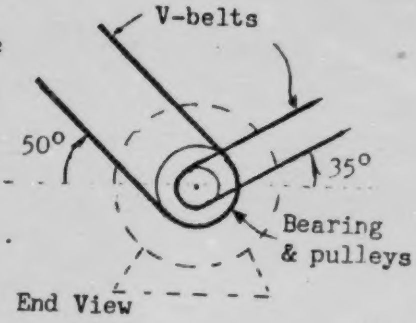
PROBLEMS CONTINUED

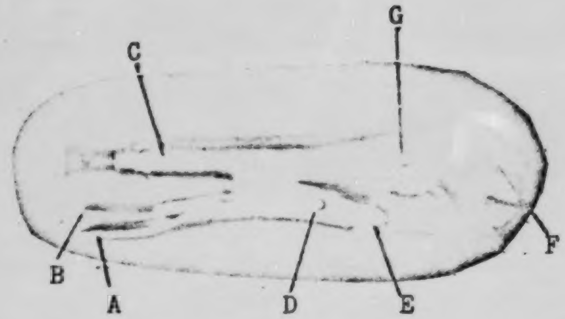
13. 

Toggle Joint

A toggle joint has arms AB and BC of 12 inches each. If each arm makes an angle of 12° each with the horizontal, what force is exerted on the plunger when the pulling force is 500 lb? What is the force when the angle is 5°?

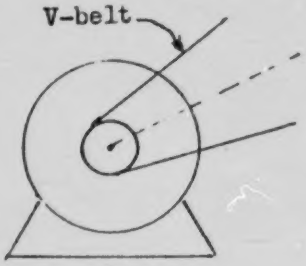
14. Tension in the v-belts (see diagram) are 87.5 lb in direction A on each side, and 64.0 lb in direction B on each side when the motor is at rest. The pulleys are on the end of a motor armature shaft which operates on a bushing. What force (magnitude and direction) does the shaft exert on the bushing? Assume the pulleys and bearing are coincident so a direct pull results.



15. 

The parts of a vise-grip (ED and DC) form a toggle joint (see problem 13). A force is applied at the joint (D) by the action of lever AD. Approximately 7 lb of force is required at point A on the handle to close the vise-grips snuggly with one hand. This translates to about 25 lb on th toggle joint. The force on E, which provides the clamping action at the jaws (F), is about 125% greater than that at the center of the jaws. Find the force E if 25 lb is applied at the toggle joint (D). The angle between ED and DC is 178.8°. Assume the line of action of the force bisects the angle. What is the force at the center of the jaws?

16. Find the side force on the inner race of a ball bearing due to 156 N of tension (each side) in a v-belt that makes an angle of 16.8° between it and the line connecting the drive and driven pulleys.



## PROBLEM ANSWER KEYS

## Module M 3 THE NATURE OF VECTORS

1. Equal magnitude, opposite direction
2. No
3. Yes, if directions are correct and if one is not greater than the sum of the other two.
4. No
5. Scalar, distance traveled
6. 175 N, 25 N
7. 2470 east, 1430 south
8. 264 lb, 222 lb
9. a, b, c, g
10. 7.43 miles west, 3.47 miles south
11. Zero
12. 2170 lb at 0.53° from positive x-axis
13. 1180 lb, 2830 lb
14. 207 lb at 91.9° from x-axis
15. 1193 lb, 954 lb
16. 299 N

EXPERIMENTS

## Module M 3 THE NATURE OF VECTORS

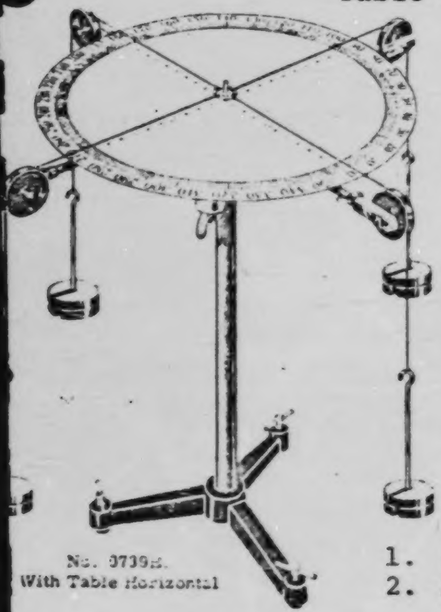
PURPOSE: The purpose of this experiment is to study the vector sum of several concurrent forces, to evaluate the equilibrant of the forces, and to study the resulting equilibrium.

CAUTIONS:

1. Read all of the instructions before handling any of the equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using.
3. Observe all cautions listed in the procedure section of these instructions.

INFORMATION: A set of forces, acting on the same object, whose line of actions all intersect at the same point is said to be a concurrent set of forces. The vector sum of a set of concurrent forces is called the resultant and the same results will be obtained. An additional force called the equilibrant of the set of forces is equal in magnitude but opposite in direction to the resultant. Both the resultant and the equilibrant are concurrent with the original set of forces. When the equilibrant is applied to the object along with the original set of forces, the object comes to an equilibrium situation. Graphical and analytical methods of finding the resulant and equilibrant are described in your textbook or in the information sheet, page , of this booklet.

Equipment: Sargent Welsh, catalog number 0739B, Kennon Force Table consisting of the following parts (see Fig. 1):



No. 0739B.
With Table Horizontal

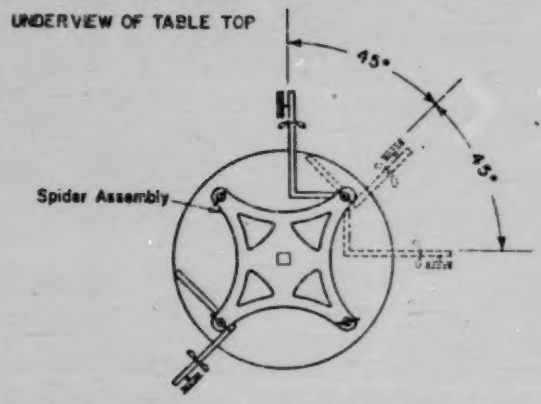
1. Table top with a 360° circle etched on the surface.
2. Pulleys and pulley support rods.
3. A support rod and tripod base.
4. Accessories consisting of weight hangers, metal ring, string, slotted weights, and small level.

Check to see that all the equipment is available before you start. Ask your instructor if you have any questions about the equipment.

PROCEDURE:

1. Place the aluminum disc on a table with its face down.
2. Adjust the pulleys so that they are pointed radially outward from the center of the table top. Observe that the position of each pulley can be adjusted 45° on each

side of the spider arm to which it is attached. Note that when a pulley is pointing radially outward near the spider arm, it is clamped near the bend in the pulley support rod. When a pulley is pointing radially outward between two spider arms, it is clamped near the end of the pulley support rod (see Figure 2).



A pulley can be mounted at any point on the 360° disc

Figure 2.

3. Make the adjustments so that three pulleys are at about 0°, 50° to 75° and -100 to -130°. Leave the fourth pulley for later adjustment. Mount the support rod on the tripod base.
4. Mount the table on the support rod in the horizontal position. For the horizontal position, the axis of each pulley wheel must be parallel to the plane of the table and perpendicular to the axis of the table.
5. Level the assembly using the leveling screws in the base.
6. Attach strings to the metal ring and weight hangers and place the strings in the grooves of the pulleys as shown in Figure 1 with the metal ring on the center peg.
7. Place slotted weights of unequal amounts on the three hangers. Use 100 g to 400 g including the 50 g weight of the hanger.
8. Record the three forces (magnitude and direction) in the table on the data sheet.
9. Make a vector polygon of the three forces. Estimate the resultant.
10. Use the analytical method and determine the resultant and equilibrant (magnitude and direction).
11. Adjust the fourth pulley so the fourth string will pull in the direction of the equilibrant.
12. Add weight to the fourth hanger equal to the magnitude of the equilibrant.
13. Test for equilibrium as follows: Equilibrium will be attained when the ring is at rest at the center of the table. Raise the ring a few centimeters above the force table and release it. If the ring returns to the center, equilibrium has been established and the friction in the pulleys is a minimum. If the ring does not return to the center, the forces are not in equilibrium and you should repeat your calculations.
14. Write down your conclusions and observations in the space provided on the data sheet.

"Diagrams and part of the written material in the equipment and procedure section used by permission from Sargent-Welch Scientific Company, Instructions for the use of Kennon Force table."

# Applied Physics Module

**SOUTHEAST COMMUNITY COLLEGE—Milford Campus** Milford, Nebr. 68405

Module: M 4

Title: Static Equilibrium

Module Contents:
1. Moment of force (torque)
2. Center of gravity
3. Types of equilibrium
4. Equilibrium (parallel forces)
5. Equilibrium (non-parallel, non-concurrent forces)

Program: This unit has been prepared especially for students in:

1. Manufacturing engineering technology
2. Machine tool and design technology
3. Welding technology
4. Industrial plastics technology
5. Electromechanical technology

Purpose: The purpose of this module is to extend the study of vector addition and resolution. The laws of static equilibrium in two dimension are introduced. Applications involving welded trusses, hoists, jig cranes, mechanical links, etc., are included.

Producer: Gene Waring

Date Produced: August 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

## Module M 4 STATIC EQUILIBRIUM

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define the following words or terms: moment, turning moment, torque, moment of force; center of rotation, moment center or fulcrum; center of gravity; moment arm or lever arm; and equilibrium.
2. Construct free body diagrams and vector diagrams for specific rigid body problems.
3. Recognize the greek capital letter sigma and state the mathematical meaning it represents.
4. State the two conditions of equilibrium.
5. Use the laws of equilibrium to solve practical problems (parallel forces) including the location of the center of gravity.
6. Use the laws of equilibrium to solve structural problems including the location of the center of gravity ( non-parallel, non-concurrent forces).

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of equilibrium. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 5 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4 ).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook and the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 8 ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks. (For those using texts B and D only)

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read part of chapter 5, pages 121-125, sections 5.8 and 5.9. Also read information sheets.

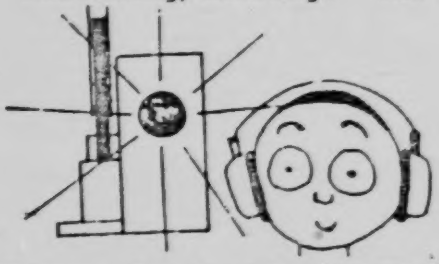
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read all of chapter 4, pages 37-44.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 13, pages 174-180 and information sheets.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read part of chapter 10, pages 119-126 and 130-138. (Omit section 10.6)

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read part of chapter 7, pages 94-100. (Omit section 7-1)

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Tacoma Narrows Bridge Collapse, (BFA Ealing 80-2181) QC/122/L49x/#8
B. The Center of mass, (BFA Ealing - 3148) QC/122/M462x/#1
C. Dynamics Response of a Suspension Bridge, (AAPT Physics film #17)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page 10 ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving equilibrium of rigid body problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about torque, center of gravity, and equilibrium.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given) Obtain a laboratory data sheet (M-4) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

## Module M 4 STATIC EQUILIBRIUM

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The magnitude of a moment of force depends on how far the force is from the center of gravity.

T - F 2. A group of parallel forces cannot be concurrent.

T - F 3. The vector sum of the forces acting on an object in equilibrium must be equal to zero.

T - F 4. It is not possible for: "an object to be in linear equilibrium but not rotational equilibrium at the same time."

T - F 5. A body that remains at rest is said to be in a state of static equilibrium.

6. The unit of torque in the British measuring system is:

a) ft/lb
b) lb·ft
c) $lb \cdot ft^2$
d) lb/ft

7. Which of the following group of parallel forces cannot be in equilibrium?

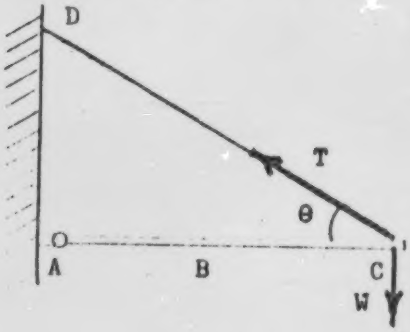
a) 7, 14, and 21 N
b) 3, 7, and 4 lb
c) 10, 40, and 20 dynes
d) 15, 30, 15 oz

8. A uniform steel rod is 3 m long and weighs 125 N. It has a load of 175 N attached at one end. The balance point from the loaded end in centimeters is:

a) 62.5
b) zero
c) 210
d) 100

9. A 36 ft, 400 lb utility pole has its center of gravity 14.5 ft from the heavy end and rests on supports at each end. Two 265 lb loads are located at 10 ft and 25 ft, respectively from the heavy end. What are the reactions at each end?

10.



A 70 N horizontal bar (AC) is 3 m long and has its center of gravity at B, 75 cm from pin A. A weight of 250 N is located at C on the end of the bar. The angle is 65°. Find the tension in the cable (CD).

## ANSWER KEY TO THE SELF-EVALUATION TEST

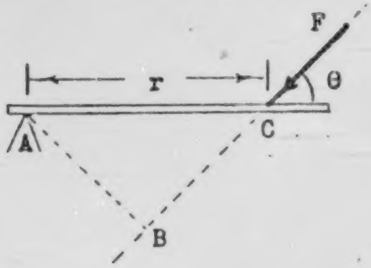
Module M 4 STATIC EQUILIBRIUM

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. F | I. Reading or II. Listening/Viewing |
| 2. T | I. Reading |
| 3. T | I. Reading or III. Solving Problems |
| 4. F | I. Reading or III. Solving Problems |
| 5. T | I. Reading |
| 6. b | I. Reading or III. Solving Problems |
| 7. c | III. Solving Problems or V. Performing Laboratory Experiments |
| 8. a | III. Solving Problems or V. Performing Laboratory Experiments |
| 9. 511 lb, 419 lb | III. Solving Problems or V. Performing Laboratory Experiments |
| 10. 295 N | III. Solving Problems |

INFORMATION SHEET

Module M 4 STATIC EQUILIBRIUM

The following information is included for those students using textbooks A and C (See STUDENT INSTRUCTIONS, page ). These text do not cover objective #6 (STUDENT INSTRUCTIONS, page ) dealing with non-parallel, non-concurrent force problems.



MOMENT OF FORCE

The moment of force (torque) on an object is the product of the force and its moment arm (lever arm). When a force is applied to an object as in Figure 1, it acts along a line CB called the line of action of the force. The moment arm is the shortest distance between the axis of rotation or fulcrum to the line of action. Thus: the moment arm for force F in Figure 1 is the distance AB. It may be calculated by the formula: $AB = r \sin \theta$. The moment of force or torque (T), therefore, is:

$$T = Fr \sin \theta$$

You can readily see that the torque does depend on the angle at which the force is applied. The torque on a wrench, for example, is greatest when the force is applied perpendicular to the handle ($\theta = 90°$).

EQUILIBRIUM (non-concurrent, non-parallel forces)

The laws of equilibrium for co-planar forces are:

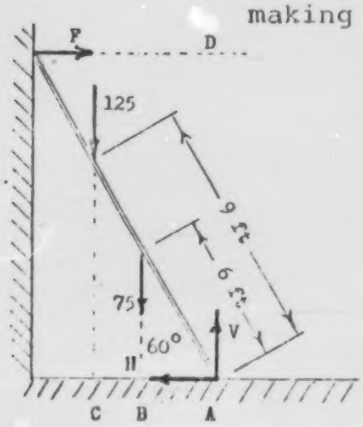
1. $\Sigma F_x = \Sigma F_{-x}$
2. $\Sigma F_y = \Sigma F_{-y}$
3. $\Sigma T_{cw} = \Sigma T_{ccw}$

The following examples illustrate the application of these laws to non-parallel forces.

EXAMPLE 1: A 16 ft, 75 lb ladder has its center of gravity 6 ft from the bottom end. It leans against a building making a 60° angle with the ground. A woman weighing 125 lb stands on a rung 9 ft from the bottom end. Find the horizontal (H) and vertical (V) components of the force exerted on the ladder by the wall. Assume the wall is frictionless so that F is horizontal. Write the three laws as they apply to this problem:

1. F = H
2. V = 125 + 75

Choose the fulcrum to be at the lower end of the ladder so forces V and H



exert no torques and are thus eliminated from equation three:

3. (75 x 6 cos 60°) + (125 x 9 cos 60°) = F x 16 sin 60°

Note that 6 cos 60 is the distance AB, 9 cos 60 is the distance AC and 16 sin 60° is the distance AD.

Now observe the three equations. F is the only unknown in equation 3, V is the only unknown in equation 2, and can be solved immediately: F = 56.8 lb, V = 200. From equation 1 we see that H = F = 56.8 lb.

EXAMPLE 2: A 7 x 3 ft, 60 lb door hangs from two hinges. One hinge is 1 ft from the top; the other is 1 ft from the bottom. The center of gravity is at the geometric center of the door. Find the horizontal and vertical components of the reactions on the hinges if the lower hinge supports 2/3 of the weight of the door.

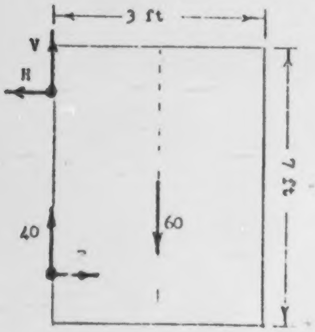


Figure 3

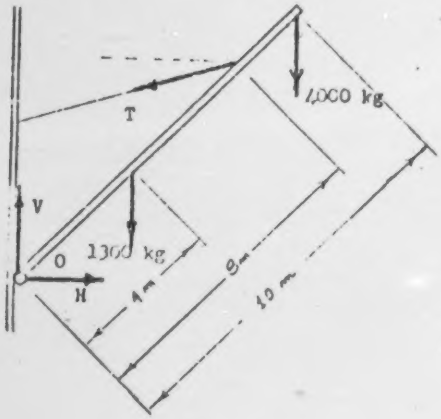
Note that 2/3 of the weight is 40 lb so the vertical component of the lower reaction is 40 lb. Write the three equations applied to this problem:

1. H = F
2. V + 40 = 60

Choose the fulcrum at the upper hinge to eliminate V and H from the third equation. Note that this also eliminates the 40 lb force since its line of action passes through the fulcrum and therefore has a zero lever arm. 3. F x 5 = 60 x 1.5 Note that the 5 ft is the distance from the fulcrum (upper hinge) to the line of action of F, and the 1.5 ft is the distance from the fulcrum to the line of action of the door's weight. Now, observe the three equations: F can be found in equation 3, V in equation 2, and H in equation 1 after F is found. F = 18 lb, V = 20 lb, and H = 18 lb.

EXAMPLE 3: A derrick (see Figure 4) has a 10 m boom weighing 1300 kg. A load of 4000 kg hangs from the end of the boom. A cable supports the boom 2 m from the end and pulls at a 30° angle below the horizontal, the center of gravity of the boom is 4 m from the lower end. Find the horizontal and vertical reactions at the lower end of the boom and the tension in the cable. The boom makes as 45° angle with the horizontal.

Figure 4



Choose the lower end of the boom as the fulcrum to eliminate V and H from the third equation.

1. H = T cos 30°

2. V = 4000 + 1300 + T sin 30°

3. (1300 x 4 cos 45°)+(4000 x 10 cos 4
= (T·8 cos 15°)

Note the lever arm for T is from the lower end of the boom (fulcrum) to point B in space to the left of the mast. Study the diagram to see how the magnitude of its lever arm is determined ( 8 cos 15°) Solving:

$$T = 4140 \text{ kg}$$
$$H = 3580 \text{ kg}$$
$$V = 9440 \text{ kg}$$

This problem could have been solved by writing the third equation in terms of the horizontal and vertical components of the tension which would have been:

$$(1300 \times 4 \cos 45^\circ) + (4000 \times 10 \cos 45^\circ) + (T \times 8 \sin 30^\circ \cos 45^\circ) = (T \times 8 \cos 30^\circ \cos 45^\circ)$$

PROBLEMS

Module M 4 STATIC EQUILIBRIUM

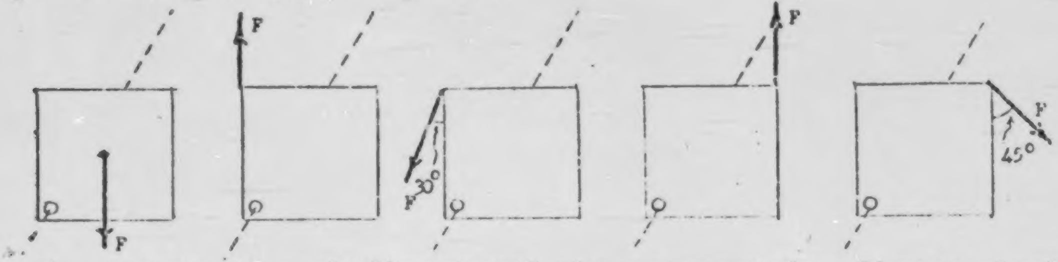
1. Why is a truck piled high with hay more likely to upset on a hillside than one loaded with the same weight of a more dense material such as crushed rock? Explain using vector diagrams.

2. A force of 40 lb is applied perpendicular to a wrench handle which is 16 in long. What torque is applied? If the force were applied at an angle of 60° to the handle, what is the torque?

3. A spring balance "weighs" up to 2000 g. How could you use it and a meter stick to find the mass of a 10 000 g object?

4. What advantage does an automobile brake drum with a large diameter have over one with a small diameter?

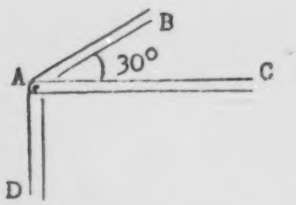
5. A full oil drum is tipped to one side. Its diameter is 18 in long and its height is 32 in. What is the smallest angle the drum's axis can make with the horizontal without falling over? Explain using vector diagrams.



6. Is the torque on each diagram of the accompanying figure clockwise, counter-clockwise, or zero?

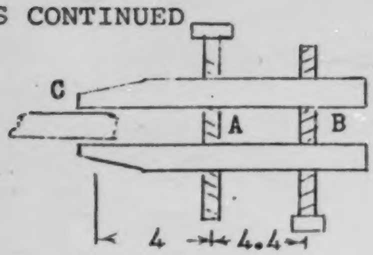
7. If the squares in problem 6 are each 2 ft on a side, and the force is 10 lb in each case, calculate the torque for each.

8. Trusses are used in such structures as TV towers, truck frames, and large roofs. The force in each member of a truss must be found so the member can be made large enough to carry two loads in it. These forces can be found by determining the forces acting on the pin at each joint. Tensile forces pull and compressive forces push on the joint. Find the forces in members AB and AC if the compressive force in AD is 10 000 N. Note that these forces are concurrent.



9. A 16 ft I beam is supported by columns at each end. A chain hoist is attached and can move along the beam on rollers. If the hoist and load combined is 1200 lb, and is located 7 ft from one end, find the reactions on the column. The beam is uniform and weighs 1040 lb.

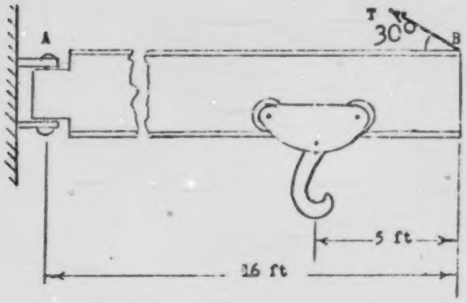
PROBLEMS CONTINUED

10. 

A toolmaker's parallel clamp is exerting a force of 420 N at C. Find the forces in the two screws at A and B on the upper jaw. Assume the jaws are parallel. Dimensions are in centimeters

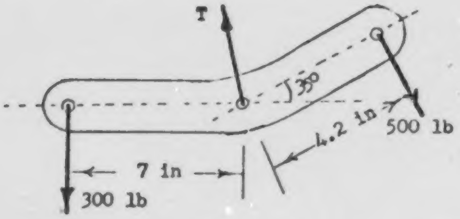
11. An 8 ft long, uniform table cart with large wheels is used to move small equipment around in a machine shop. It weighs 180 lb. A 90 lb blanking die is placed so its center of gravity is 2 ft from one end. What reaction is there on the four wheels?

12. A uniform metal sign on the front of a welding shop is 4 ft high and 8 ft long and weighs 140 lb. The inside top corner is held to the wall by a horizontal pin and by a guy wire which is fastened to the outer top corner and runs to a point 5 ft above the pin. Calculate the tension in the guy wire and the horizontal and vertical components of the force on the pin.

13. 

A jig crane allows the hoist mounted at hook C to swing about pin A and the hoist can move on rollers along the I beam. Find the horizontal and vertical components of the force exerted on the I beam by the pin at A and the tension in the cable at B if a load at C of the jig crane is 2800 lb. The beam weighs 1040 lb.

14. The gate at the entrance of an iron works yard has a tubular frame and is covered with fencing. It is uniform and weighs 530 lb. It is 8 ft high and 12 ft long and has hinges 1 ft from the top and 1 ft from the bottom. Find the horizontal and vertical components of the force exerted on the gate by each hinge if the lower hinge carries three-fifths of the weight.

15. 

Find the horizontal and vertical components of the reaction on the pin for the link shown by calculating moments. Find the magnitude and direction of the reaction. Are the three forces on the link concurrent?

## PROBLEM ANSWER KEY

## Module M 4 STATIC EQUILIBRIUM

1. Higher center of gravity. Line of action of weight moves outside wheels at small tilt angle.
2. 53.3, 46.2 ft lb.
3. Place spring near pivot.
4. Braking force has larger lever arm.
5. 29.4°
6. cw, o, ccw, ccw, cw
7. 10, 0, 10, 20, 28.3 ft lb
8. 20 000 N downward along member, 17 300 N to the right.
9. 1195, 1045
10. 801 N, 382 N
11. 56, 56, 79, 79
12. T = 132, H = 112, V = 70
13. T = 4890, H = 4230, V = 1395
14. Upper: V = 212, H = -454, Lower: V = 318, H = +454
15. V = 710, H = 287, R = 765 at 23° left of vertical. Yes.

## Module M 4 STATIC EQUILIBRIUM

**PURPOSE:** The purpose of this experiment is to study non-concurrent, parallel, coplanar systems of forces acting on a rigid body and to study and measure the location of the center of gravity of a rigid body.

**CAUTIONS:**

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

**EQUIPMENT:** Check to see if all the following equipment is available before you start.

1. One meter stick
2. One slotted weight with clamp (Welch #1154H)
3. Two lever knife-edge clamps (Welch #0745)
4. Two 100 gram knife-edge weights (Welch #0743E-36)
5. One 50 gram knife-edge weight (Welch #0743E-30)
6. One dial spring scale (2000 gram)
7. Two supports with grooves for knife-edge clamp (Welch #0743C)

**PROCEDURE:**

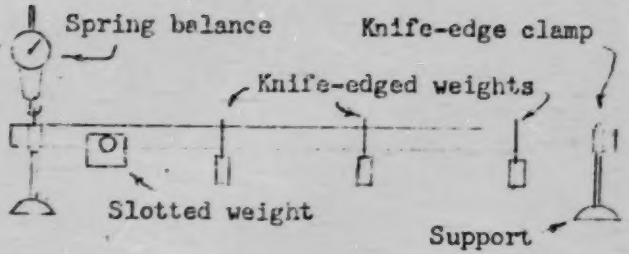
1. Weigh the knife-edge clamps and record on the data sheet.
2. Mount the knife-edge clamps at the 30 cm and 90 cm marks on the meter stick. The pointer on the clamps indicate the exact setting.
3. Mount the sliding weight at approximately the 15 cm mark on the underside of the meter stick.
4. Place the meter stick so the knife-edge rests in the grooves of the supports. Place a 100 g knife-edge weight at about the 80 cm mark to hold it down.
5. Place the other 100 g and the 50 g knife-edge weights between the supports.
6. Record the exact position of the knife-edge weights in the table on the data sheet.

**CAUTION:** A slight jar will cause the knife-edge weights to move so be sure to check their position each time a measurement is made.

**NOTE:** The object of this experiment is to find the center of gravity and the weight of the meter stick-slotted weight combination excluding all other weights and clamps.

PROCEDURE CONTINUED

7. Attach a dial spring balance to the wire stirrup of the knife-edge clamp near the slotted weight.



8. Lift the balance until the meter stick just raises off the support. Record the spring scale reading.

9. Subtract the weight of the knife-edge clamp and record the reaction ($R_1$) in the table. Refer to the accompanying diagram.

10. Repeat problems 8 and 9 for reaction $R_2$.

11. Calculate the location of the center of gravity (x) and the weight of the meter stick-slotted weight combination using the laws of equilibrium (see text). Record this information on the data sheet.

12. Remove all clamps and weights except the slotted weight from the meter stick.

13. Weigh the meter stick-slotted weight combination with the spring scale.

14. Compare calculated weight and measured weight. Record the percentage of error.

15. Attach a knife-edge clamp, sliding it back and forth until it balances when supported (in your hand) by the wire stirrup.

16. Compare the measured and calculated positions of the center of gravity. Record the difference in millimeters.

# APM Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 5

Title: MOVIN' ON

Module Contents:
1. Displacement, velocity and acceleration
2. Constant velocity motion
3. Accelerated motion
4. Acceleration of gravity and vertical motion

Program: This module was produced especially for students in:
1. Manufacturing engineering technology
2. Machine tool and design technology
3. Welding technology
4. Industrial plastics technology

Purpose: The purpose of this module is to study linear motion - motion along a straight line in which no more than one reversal of direction takes place. The feeding movement of the saddle on a lathe is one example of such motion. Other examples are: Belts moving between pulleys, a mobile welding unit traveling to the job, a band saw speeding past a workpiece and moving conveyors.

This module is prerequisite for other modules that describe force, energy, etc.

Producer: Gene Waring

Date Produced: August 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## Module M 5 MOVIN' ON (Motion)

## OBJECTIVES

When you have satisfactorily completed this module you will be able to:

1. Define the words: displacement, velocity, average velocity, and acceleration, state the symbol that represents each, and state the British, mks and cgs units of each.
2. Convert units of velocity from one measuring system to another.
3. State the four equations that describe uniform accelerated motion.
4. Solve various constant velocity and average velocity problems.
5. Solve various problems of uniform accelerated motion, including those involving deceleration and vertical motion; and including those in which one change in direction might take place.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of motion. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5 ) along with an answer key. You can evaluate your previous knowlege of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions, correctly. The answer key page (pink, page 6 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4 ).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook and the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper, (page 7 ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read part of chapter 3, pages 43-59.

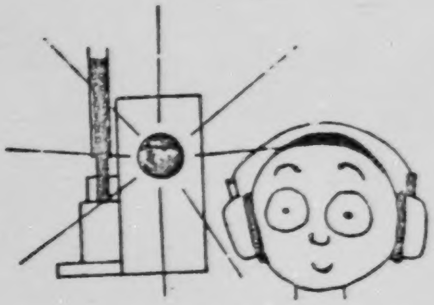
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read part of chapter 5, pages 49-55.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 3, pages 29-38 and all of chapter 5, pages 47-53.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1966. Read part of chapter 3, pages 23-37.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read all of chapter 3 and part of chapter 4, pages 35-54.

II. Listening/Viewing: The following single-concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the projection and sound equipment (Viewlex 702 or Technicolor) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. How an Air Track Works (BFA Ealing 80-280)
B. Constant Velocity and Uniform Acceleration (BFA Ealing 80-272)
C. One Dimensional Motion (BFA Ealing 80-300)
D. The Velocity Vector (BFA Ealing 80-251)
E. The Acceleration Vector (BFA Ealing 80-253)
F. Velocity and Acceleration in Free Fall (BFA Ealing 80-256)
G. Acceleration Due to Lunar Gravity (AAPT/NASA Films -20)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Work as many of them as you feel are necessary to gain competence in solving motion problems.

IV. Solving Problems (Optional) Solve some of the problems at the end of the chapter in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are two experiments in this module. One experiment covers uniform velocity; the other covers uniformly accelerated motion. Both experiments are performed on an air track.

Read the laboratory instructions in the booklet (yellow paper, page 13 ) and pay particular attention to the cautions given. Obtain a laboratory data sheet (M-5) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

Module M 5 MOVIN' ON (Motion)

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. A screwdriver dropped from rest will fall four times as far in 2 s as it does in 1 s.

T - F 2. An automobile having a speed of 55 miles per hour travels 240 miles in 4 hr.

T - F 3. The downward acceleration of a metal ball depends on whether it was thrown upward or thrown downward.

T - F 4. An elevator moving upward comes to a stop. Its acceleration is downward.

T - F 5. The acceleration of gravity is $3.2 \times 10^2$ ft/s$^2$.

6. An automobile goes from 15 miles per hour to 55 miles per hour with uniform acceleration. Its average velocity is:

a) 30 mi/h
b) 40 mi/h
c) 35 ft/s
d) 51.3 ft/s

7. A car has an initial velocity of 40 ft/s and an acceleration of -4 ft/s$^2$. In 10 s it travels how many feet?

a) 100
b) 200
c) 360
d) 300

8. Sixty miles per hour is equivalent to:

a) 96.1 km/h
b) 44 ft/s
c) 66 ft/s
d) 37.5 km/h

9. If an elevator can accelerate at 3 m/s$^2$ to a maximum speed of 4.3 m/s, how far upward will it go in 10 s starting at rest?

10. Find the displacement after 4 s of a steel ball thrown vertically upward with an initial speed of 90 ft/s. Is it still going upward or is it on the way back down?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 5 MOVIN' ON (Motion)

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. T | I. Reading or II. Listening/Viewing |
| 2. F | III. Solving Problems V. Laboratory Experiments |
| 3. F | I. Reading |
| 4. T | I. Reading or II. Listening/Viewing |
| 5. F | I. Reading |
| 6. d | I. Reading III. Solving Problems |
| 7. b | III. Solving Problems V. Laboratory Experiments |
| 8. a | III. Solving Problems |
| 9. 39.9 m | III. Solving Problems V. Laboratory Experiments |
| 10. 104 ft ↓ | III. Solving Problems V. Laboratory Experiments |

INFORMATION SHEET

Module M 5 MOVIN' ON (Motion)

Study the table below which lists the four formulas for constantly accelerated motion. Note that in the four formulas there are five quantities: time (t), displacement (s), initial velocity ($v_0$), final velocity (v), and acceleration (a). Note, also, that one quantity is missing from each equation, but, that the initial velocity is found in all four.

| | FORMULA | SYMBOL OMITTED |
|---|---|---|
| 1 | $a = \frac{v - v_0}{t}$ | s |
| 2 | $s = \frac{(v + v_0)}{2} t$ | a |
| 3 | $v^2 = v_0{}^2 + 2as$ | t |
| 4 | $s = v_0 t + \frac{1}{2} at^2$ | v |

Mathematically speaking, only two of the four equations are unique. The third and fourth equations can be derived from the first two (for example) by eliminating other variables. All of this means that you can solve for only two unknown quantities and that the other three must be given in the problem.

Sometimes it is not readily apparent in a problem that three quantities are given (or known). You must keep in mind, however, each of the four equations contains four quantities. Three must be given in order to solve for the fourth. Some statements and their meanings are:

1. "An object starts from rest" means $v_0 = 0$
2. "A body comes to a stop" means $v = 0$
3. "The beginning speed is 25 mi/hr and the speed doubles" means v = 50 mi/hr
4. "A falling body . . ." means $a = -32$ ft/s$^2$ or $-9.8$ m/s$^2$
5. "A body thrown upward returns to its starting point" means $s = 0$
6. "How high does an object go . ." means $v = 0$

There are four quantities in each of the four formulas. None contains the same set of four quantities. Thus, with three given and one unknown, you really have no choice in finding the solution. Only one equation will work!

After you have evaluated the fourth quantity, things get easier. The fifth quantity can now be found by using any one of the remaining three equations. Choose, by inspection, the simplest of the three.

The following examples will illustrate the above points:

EXAMPLE: An automobile decelerates at 12.6 $ft/s^2$. If the initial velocity is 55 mi/hr, how much time does it take to get stopped and how far does it travel?

SOLUTION:

1. Since displacement, velocity and acceleration are vectors, we should first assign positive and negative directions (you can usually do this mentally). Choose the forward direction as positive.
2. Make a list of knowns. $a = -12.6\ ft/s^2$; $v_0 = +80.7\ ft/s$; $v = 0$; $t = ?$

   From this list it is easy to see that equation 1 is the only one we can use since all others have displacement (s) in them, and we do not know its value.
3. Solve equation 1 for time: $t = (v - v_0)/a$
4. Substitute the numbers and evaluate:

$$t = \frac{0 - 80.7\quad /s}{-12.6\ ft/s^2} = 6.4\ s$$

5. Equation 2 appears, at first glance, to be the easiest to use for solving for distance:

$$s = \frac{(0 + 80.7\ ft/s)}{2}(6.4\ s) = 258\ ft$$

EXAMPLE: A hammer is thrown at 30 m/s. Where is it 5 s later and what is its velocity?

SOLUTION:

1. Take upward as positive.
2. List: $a = -9.8\ m/s^2$; $v_0 = +30\ m/s$; $t = 5\ s$; $s = ?$
3. Choose equation 4, substitute and evaluate the displacement:

$$s = v_0t + \tfrac{1}{2}at^2 = (30\ m/s)(5s) + \tfrac{1}{2}(-9.8\ m/s^2)(5s)^2$$
$$= 150\ m - 123\ m$$
$$= +27\ m$$

4. Choose equation 1, solve, substitute and evaluate the velocity:
   $v = v_0 + at = 30\ m/s + (-9.8\ m/s^2)(5s) = -19\ m/s$

## FALLING BODIES

Falling bodies are normally moving through air, near the surface of the earth. Except in a near vacuum, there are several forces besides the pull of gravity. They are:

1. Friction: Depends on the speed and shape of the object. It increases as the object goes faster and faster. It is always in a direction opposite to that of the motion.

2. Buoyancy: Depends on the density of the air. It is usually negligible except on low density objects such as balloons. It is always upward.

3. Bernoulli forces: Depends on air flow around the object and causes sideways pressure. The fluttering of the leaves as they fall is one example.

4. Gravity: Depends on distance between the center of the earth and the center of the object. It may depend on local variations of gravity. Its direction is always downward.

5. Magnetic forces: If an object becomes electrically charged as it falls, the Earth's magnetic field could cause a sideways deflection.

At the beginning of free fall, gravity is the overriding force except on balloons and other light objects. When the speed increases friction also increases, partially cancelling the pull of gravity. At faster and faster speeds friction increases until it equals the pull of gravity. During this time the acceleration decreases gradually to zero and the object falls at a constant speed (terminal velocity) from then on. On some objects the other forces may be important.

Different objects fall for different times during the transition and attain different terminal velocities. The four equations of motion for falling bodies give correct results for a few seconds for most fairly dense objects. A skydiver, for example, falls 16 ft during the first second, the same as predicted by equation 4. He falls 6 ft short of the 144 ft predicted by the equation at the end of the 3rd second (4.3% error).

A skydiver falls face downward, arms and legs spread. With his parachute and floppy clothes, he is a falling object that offers a lot of resistance to motion. He reaches a terminal velocity of 174 ft/s at the end of 11 s. Other objects offering less resistance may fall several seconds with almost no deviation in the distance and speed as predicted by the equations. A 5 in polished metal sphere, for example, will fall more than a minute before reaching terminal velocity. The terminal velocity would be over 350 ft/s and the sphere would have fallen more than a mile before reaching it.

The above information is to give you an indication of when the equations give correct results. The problems in the problem set are realistic within small percentage errors.

## PROBLEMS

## Module M 5 MOVIN' ON (Motion)

1. Explain the relationship among an object's initial, final and average velocities if the motion is (a) uniform velocity, (b) uniform acceleration.

2. Give an example of the circumstances when an object can have (a) a velocity but no acceleration, (b) an acceleration but no velocity.

3. A wrench thrown vertically upward is accelerated by gravity before it reaches its peak, at the peak and on its way back down. Explain the difference between the expressions "instantaneous zero velocity," "an object at rest or stopped." What is the acceleration and velocity at the peak of the flight?

4. A mobile welder on a truck, on its way to repair some farm equipment, traveled 5.5 mi in 8.3 min. What is the average speed in miles per hour? If the same average speed is maintained, how much more time is required to travel the remaining 14.5 mi to the farm?

5. A machinist, going home from work, traveled 4 blocks north, then 7 blocks east, then 2½ blocks north. If it took him 11.4 min (including stops at one stop sign and one traffic light), find his displacement, distance traveled, average speed, and average velocity. (Assume 10 blocks equal 1 mile)

6. A band saw has a surface speed of 20 in/s when used to cut die steel. If the blade has ten teeth per inch, how many teeth move past the cutting table in 5 min? How much time is required for 1000 ft of blade to move past the cutting table?

7. The distance a cutting tool feeds when turning a 2 in cast iron rod in a lathe is 0.070 in/s. How much time is required to turn a 1.5 ft length of the workpiece? How many feet can be turned in 5 min?

8. A shaper makes a forward stroke in 0.01 min and a return stroke in 0.00667 min while completing sixty cycles per minute. If the length of the stroke is 0.6 ft, find the forward speed, the return speed and the average speed.

9. A freight elevator in a manufacturing plant carries equipment and supplies from the basement storage area to the first floor a distance of 18 ft. The upward velocity is 0.69 ft/s, and the downward velocity is 0.45 ft/s. How long does it take for a round trip up and back? What is the average speed for the round trip? (Assume no stop was made at the top)

10. A mechanical draftsman takes an elevator to the 10th floor, 45 m high, to the company's drafting room. If the elevator accelerates (and decelerates) at 4.3 $m/s^2$ to a maximum speed of 3 m/s, find the time required to go to the 10th floor from ground level.

PROBLEMS CONTINUED

11. A welder returning to the repair shop from a farm repair job was traveling 55 mi/h. As he came to a railroad crossing, he noticed a train approaching. He applied the brakes at a point 225 ft from the crossing. The deceleration was 15 ft/s$^2$. Was he able to avoid a collision?

12. A plastics technician was returning home from a long day on the job. He was going 50 mi/h as he crested a small hill. A farm tractor going 8 mi/h in the same direction approached a narrow bridge. The technician first noticed the tractor when he was 210 ft away. Was he able to stop in time?

13. A welder working at a height of 50 ft, repairing a damaged tower, drops a wrench. How much time does it take for the wrench to hit the ground? How fast is it going when it hits?

14. A welder working from a man-lift on a tower loses his balance. In the act of catching himself, a short piece of angle iron is thrown straight upward at a velocity of 15 m/s. It takes 4 s for the angle iron to hit the ground after just missing the man-lift on its way down. What is its speed when it hits the ground? How high was the man-lift above the ground?

15. A welder working on a bridge dropped a clamp. It hit the water below 3.5 s later. How high is the bridge? How fast was the clamp going when it hit?

ANSWER KEYS (PROBLEMS)

Module M 5 MOVIN' ON (Motion)

1. a) Same, b) $V_{av} = (v + v_0)/2$

2. a) car moving on level road at 55 mi/h
   b) object thrown straight up at peak of flight

3. a) v = 0 at a specific instant
   b) v = 0 for a period of time no matter how small

4. 39.8, 21.9 s

5. 0.955 mi at 42.9° N of E, 1.35 mi, 7.11 mi/h, 5.03 mi/h at 42.9° N of E

6. 60 000, 1 hr 40 min

7. 4.29 min, 1.75

8. 1.0 ft/s, 1.5 ft/s, 1.2 ft/s

9. 66.1 s, 0.54 ft/s

10. 15.7 s

11. Yes, 8 ft from the crossing

12. Yes, car travels 55 ft during reaction, 215 ft during deceleration but tractor moves 77.6 ft. Car stops 18 ft from tractor.

13. 1.77 s, 56.6 ft/s

14. -24.2 m/s, 18.4 m

15. 196 ft, 112 ft/s

EXPERIMENTS

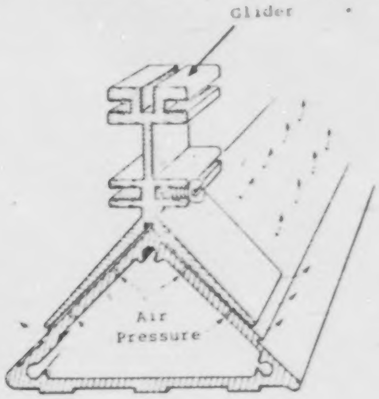
## Module M 5 MOVIN' ON (Motion)

PURPOSE: The purpose of these experiments is to study linear motion on an air track. Constant velocity and constantly accelerated motion are studied. The acceleration of gravity is measured in the second experiment.

CAUTIONS:

1. Read all of the instructions before handling any of the equipment.
2. The Basic Spark Source can cause deep painful burns as well as shock. Read and follow the instructions carefully.
3. Observe all cautions in the procedure section of these instructions.
4. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.

INFORMATION: A linear air track is used in both experiments. It is a simple device which allows you to observe motion in which there is almost negligible friction. Glides are supported so they "float" and move on a cushion of air produced by blowing air with a vacuum cleaner out of small holes on the track. The viscosity of the thin layer of air between the glider and track is the only source of friction.

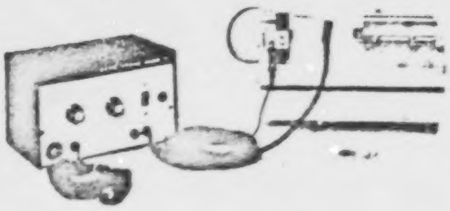


* Fig. 1 The air track

The air track is a precision device. Distances along the track can be measured to the nearest millimeter. The timing measurements needed for studying motion are made with a timing device that generates high voltage pulses at regular intervals. The resulting spark holes recorded on spark paper make a record of the position of the glides each time without affecting the motion of the glider. You should view film A (See Listening/Viewing, page 3) before proceeding with the experiment.

EQUIPMENT:

1. Student 1.2 m air track (Ealing 33-1512)
2. Two stage blower - 115 v (Ealing 33-0167)
3. Various blower hoses, couplings, tees, manifolds, etc.
4. Basic spark source - 60 Hz (Ealing 33-2403)
5. Spark tape (Ealing 33-0274)



* Fig. 2 Basic Spark Source

Check to see that all equipment is available before you start. Ask your instructor if you have any questions about the equipment.

PROCEDURE:

CAUTION: Do not plug in the basic spark source until you are ready to use it. See step 14 below. Shocks from this spark source can burn small, deep, and very painful holes in your skin. Other injuries can occur as you react to the shock. BE EXTREMELY CAREFUL NOT TO TOUCH THE SPARKING WIRE when the spark source is attached.

CAUTION: Be careful not to drop the glides. Dropping them from even a few inches height will probably ruin them. To avoid damaging surfaces, do not slide the glides on the track with the air suppy shut off.

1. Attach the air hose from the vacuum cleaner to the air track.

CAUTION: Keep the air hose on the back or side of the table so it will not be bumped. It could drag the air track off the table.

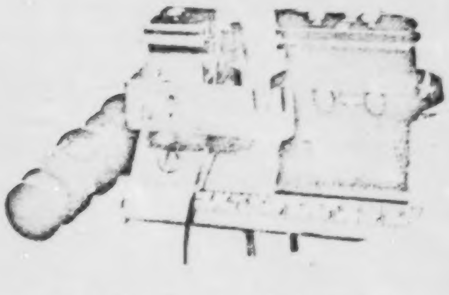
2. Plug in the air supply (vacuum cleaner) and turn it on. If only one track is being used, remove one rubber stopper from the manifold on top of the air supply. The entire supply is not needed for one track.

LEVEL THE AIR TRACK

3. Remove all gliders except one. Place one glider near the center of the track. If the track is level, the glider will not accelerate in either direction. Turn the adjusting screw knob on the air supply end of the track. Note: Slight adjustments make large changes in the glider's motion.

CAUTION: Do not bump or jar the track once it is leveled. Small irregularities in the table top will have a large effect on the gliders motion if the track is moved. Naturally, you should also avoid bumping or jarring the table for the same reason.

4. Place the gliders on the track and observe their motion including collisions with the spring bumpers. DO NOT LAUNCH THE GLIDERS WITH EXTREME VELOCITIES.



* Fig. 3 Rubber band launcher

5. Attach a rubber band to the rubber band launcher (see Figure 3). Remove all but one glider.

6. Practice launching the glider. You can vary the speed by placing the rubber bank in different slots. To reproduce the same velocity, always push the glider back until the spring bumpers just touch. Hold the glider with one finger on top. Release suddenly. Try this with both large and small gliders. Avoid touching

the spark wires. Assume it is hot even though the spark source is not attached yet.

7. Shut off the blower during set-up time.

8. Insert a strip of spark paper in the groove on the back side of the air track. A 120 cm length is sufficient. Insert the paper with the white (shiny) side up.

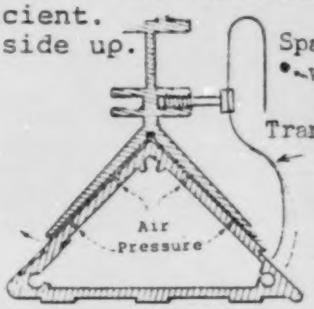


Fig. 4 *

9. If a transfer wire is not attached to the nylon post on one end of the gliders, wrap one turn of copper wire around the post and tighten. Bend the wire in the shape shown in Figure 4.

   NOTE: The transfer wire is vertical, near the sparking wire so it will not matter if the sparking wire sags a little. The bottom end of the transfer wire is placed near the upper edge of the spark paper. By bending the wire downward, more than one run can be made on one strip of paper.

10. Turn the blower on and move the glider slowly along the track. Check to see that the transfer wire does not touch the sparking wire or the spark paper. The gaps at both places should be as small as you can make them without rubbing. The sum of the two gaps should not exceed 1 cm anywhere along the track. Rubbing at either place will alter the motion of the glider.

EXPERIMENT A "Constant Velocity"

11. You are now ready to attach the Basic Spark Source. USE CARE! OBSERVE ALL CAUTIONS.

12. Attach the alligator clip leads to the air track (See Figure [illegible]
    a) Attach the large wire (hot) with the red lead to the sparking wire near the rubber band launcher.
    b) Attach the small wire (ground) with the black lead to the end stop near the rubber band launcher.

13. Set the Timing Source Selector on the 10.0 Hz position. Note that the sparks will occur 0.1 s apart.

14. You may now plug in the Basic Spark Source and turn on the panel switch but observe the following cautions:

CAUTIONS
1. Use the spark source only when recording. Do not fire it longer than necessary.
2. Never push the remote operate button without insuring a proper gap; in such a case, the discharge energy will occur internally. Continued operation without a proper gap (See Step 10) will damage the electronic components within the unit.

    3. Unplug all spark sources when making lead changes; BE SAFE, assume the unit will misfire.

15. You are now ready to make your first recording:
    a) Push the glider against the rubber band to get ready for launching. The rubber band should be in the position that gives the glider its greatest launch velocity.
    b) Simultaneously, release the glider and depress the remote operate button on the spark source.
    c) Be sure to turn off (release) the remote operate button as soon as the glider reaches the opposite end of the track to avoid making spark holes on the return trip and confusing the record.

16. Unplug the spark source. BE SAFE!

## EXPERIMENT B "Constant Acceleration"

17. Without moving the air track along the table, lift the air supply end of the track and place a block under the single leg. Use at least a one-inch thickness, three or four 100g slotted weights work very well.

18. Bend the transfer wire down so the spark will record marks near the bottom edge of the spark paper. Test for a proper gap along the whole length of the track.

19. Remove the rubber band from the launcher.

20. Plug in the Basic Spark Source.

21. You are now ready to make your second spark record.
    a) Push the glider back so spring bumper just touches the bumper on the end stop.
    b) Simultaneously release the glider and depress the remote operate button on the spark source.
    c) Be sure to turn off (release) the remote operate button as soon as the glider reaches the opposite end of the track to avoid making spark holes on the return trip and confusing the record.

22. You now have a record on spark paper for both experiments. Unplug the equipment and put it away.

23. Tape the spark paper to a table and lay a meter-stick on it edgewise so the markings are adjacent to the spark holes. Do not place the end of the meterstick on the first hole. Instead, put the one centimeter mark on the first hole and subtract it from all successive readings. Ignore the spark holes made when the rubber band was still in contact during launch.

24. Record the position of the holes for both experiments in the proper place on the data sheet.

25. Plot the data for experiment A on graph paper.

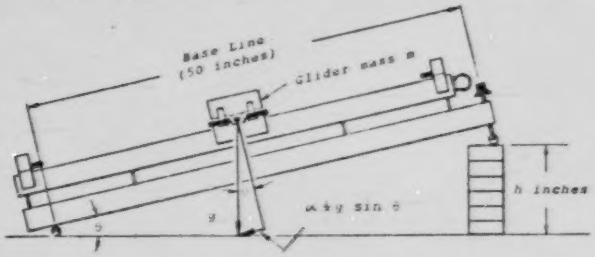
26. Calculate the speed during the first and last intervals. Does friction play a significant part during short runs on the air track? By what percentage did the velocity decrease?

27. Plot the data for experiment B on graph paper.

28. Calculate the average velocity for each interval. The average velocity for a given interval is the instantaneous velocity at the mid-point of the interval.

29. Calculate the acceleration from the mid-point of one interval to the mid-point of the next interval for each successive interval. Record in the table: $a = (v - v_0)/t$

30. Average the accelerations you have listed in the table. Note: the acceleration is shown as a vector in Figure 5. The acceleration of gravity is also shown. The sine of this angle is the ratio of height h in inches to the base line in inches (50 in).



* Fig. 5 Vector diagram

31. Calculate the sine of the angle.

32. Calculate the acceleration of gravity. $g = a/\sin\theta$.

33. Look up the standard value of the acceleration of gravity in your text.

34. Calculate the percentage difference in you calculated value and the standard value of the acceleration of gravity.

* Figures and diagrams by permission: The Ealing Corporation

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 6

Title: Friction

Module Contents:
1. The nature of friction
2. The coefficient of friction
3. Kinetic and static friction
4. Angle of repose
5. Rolling friction
6. Lubrication

Program: This module has been prepared especially for students in:

1. Manufacturing engineering technology
2. Machine tool and design technology
3. Welding technology
4. Industrial plastics technology
5. Electromechanical technology

Purpose: The purpose of this module is to introduce the concept of friction. It is a force that always acts to impede motion. It reduces efficiency of machines and great efforts are made to minimize it by using lubricants and wheels. Sometimes friction is desirable; the action of brakes and clutches depend on it. Friction is an ever present force in machines and tools used in manufacturing and fabrication industries. It is essential that you understand the nature of friction.

Producer: Gene Waring

Date Produced: September 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## Module M 6 FRICTION

## OBJECTIVES

When you have completed this module satisfactorily, you will be able to:

1. Define friction, coefficient of friction and normal force.
2. State the laws of friction for dry surfaces.
3. State the mathematical formula relating the force of friction, normal force and coefficient of friction. State the formula for calculating the normal force on an inclined plane.
4. Define the angle of repose (angle of uniform slip) and state its relationship to the coefficient of friction.
5. State the differences between limiting friction and kinetic friction.
6. State two ways in which rolling friction differs from sliding friction.
7. State the effects of lubricants on sliding and rolling friction.
8. List rolling, sliding and fluid friction in order of decreasing friction effects.
9. Solve various frictional problems, including those on an inclined plane, in which the relationships in objectives 3 and 4 are involved.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of measurement. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions, correctly. The answer key page (pink paper, page 7 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4 ).

## LEARNING ACTIVITES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. You may want to do most or all of the activities if your overall background requires it. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook and the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to learning them. Also, read the information sheet (A).

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 8 ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read sections 6.8--6.17 in chapter 6, pages 144-152.

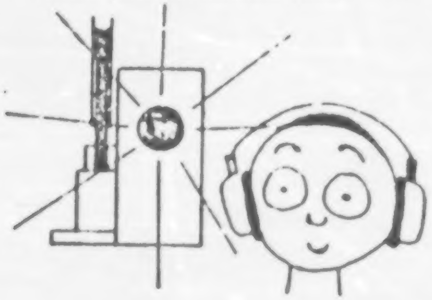
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read sections 3.5--3.9 in chapter 3, pages 30-33.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read sections 10.13--10.17 in chapter 10, pages 142-44. Also read all the information sheets (see A above).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read all of chapter 7, pages 82-90.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read all of chapter 6, pages 78-86.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Rough and Smooth, (EBE S-80781) Q/161/S2x/#3
B. Texture, (EBE S-80782) Q/161/S2x/#4
C. Rolling, (EBE S-80783) Q/161/S2x/#5
D. Wheels, (EBE S-80784) Q/161/S2x/#6

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page 14 ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving problems about friction. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about sliding friction both on flat and inclined surfaces.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M - 6) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF EVALUATION TEST

Module M 6 FRICTION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The force of friction is proportional to the normal force.

T - F 2. Changing the angle of an inclined plane will not change the coefficient of friction between the incline and the object sliding on it.

T - F 3. A 195 lb weight on a 37° incline has a normal force of 117 lb.

T - F 4. Kinetic friction is usually less than limiting friction if everthing else remains the same.

T - F 5. Lubricants can reduce kinetic friction but not limiting friction.

6. Metal containers at a manufacturing plant slide down a 27.5° incline at uniform speed. The coefficient of friction is:

a) 0.462
b) 0.887
c) 0.521
d) cannot be calculated

7. A force of 250 N is required to slide a TV set across a tiled floor. If the coefficient of kinetic friction is 0.63, how much does the TV set weigh in newtons?

a) 694
b) 397
c) 157
d) cannot be calculated

8. A crate is pulled up a 23° incline on which the coefficients of limiting and kinetic friction are 0.42 and 0.28. If the crate weighs 1200 lb, what force up the incline will start the crate moving? What force is necessary to keep it moving?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 6

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. T | I. Reading or V. Laboratory Experiments |
| 2. T | I. Reading or V. Laboratory Experiments |
| 3. F | III. Solving Problems or V. Laboratory Experiments |
| 4. T | I. Reading (Information Sheets) |
| 5. F | I. Reading or II. Listening/Viewing |
| 6. c | III. Solving Problems |
| 7. b | III. Solving Problems or V. Laboratory Experiments |
| 8. 933 lb,<br>778 lb | III. Solving Problems or V. Laboratory Experiments |

INFORMATION SHEET

Module M 6 FRICTION

Part I

## SLIDING FRICTION

For dry surfaces, friction has been found to obey the following rules:

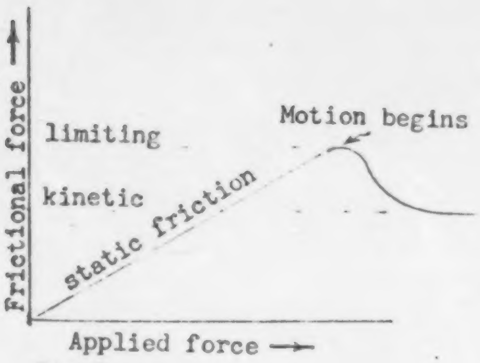


Fig 1

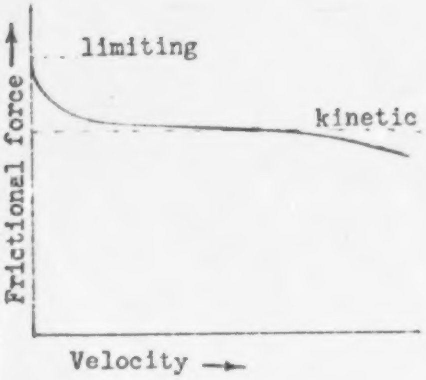


Fig 2

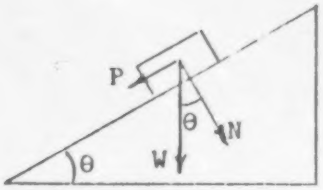


Fig 3

1. The frictional force is equal to the applied force before motion begins (see Fig. 1) and is called static friction.

2. The static frictional force is maximum just before motion begins. The maximum value of static friction is called limiting friction (see Fig. 1). Many texts use the term static friction to mean limiting friction.

3. After motion has begun, friction is usually less than the limiting friction and is called kinetic friction (see Fig. 1).

4. Kinetic friction is nearly independent of speed. It gradually decreases at higher and higher speeds, but the change is slight until extreme speeds are reached (see Fig. 2).

5. Both limiting and kinetic friction depend on the nature of the sliding surfaces.

6. Both limiting and kinetic friction depend on the force pressing the two surfaces together. This force is called the normal force (N) (see Fig. 3). On an incline the normal force is given by the equation:

$$N = W \cos \theta$$

where $\theta$ is the angle of the incline and W is the weight of the sliding object. Note that the normal force is the component of the weight that is perpendicular to the incline.

7. The frictional force is independent of the apparent contact area. The distinction between apparent and real contact area is discussed in Part II.

## THE COEFFICIENT OF FRICTION

The seven rules above describe how friction works. The source or cause of friction is described in Part II.

Rule 6 states that friction is proportional to the normal force, so:

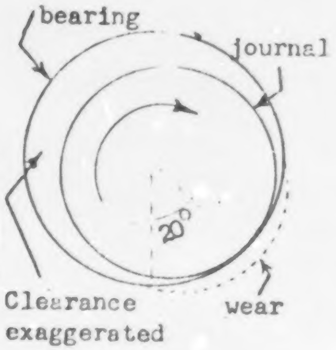
$$f = \mu N$$

Where $\mu$ is the proportionality constant and is called the coefficient of friction. The coefficient of friction depends on the nature of the two surfaces. Table 1 lists the coefficient of static friction and the coefficient of kinetic friction. For a given normal force, you can calculate the limiting or kinetic friction.

| | $\mu s$ | $\mu k$ |
|---|---|---|
| wood on wood | 0.5 | 0.3 |
| steel on steel (smooth) | 0.75 | 0.50 |
| metal on metal (lubricated) | 0.03 | 0.03 |
| rubber on dry concrete | 0.9 | 0.7 |
| rubber on wet conrete | 0.7 | 0.5 |
| plastic on steel | 0.2 | 0.2 |

(Table 1)

Fig 4



EXAMPLE 1. A car weighing 4000 lb has a coefficient of limiting friction of 0.9 between tires and concrete. What is the maximum braking force that can be applied without skidding?

$f = \mu N = 0.9\ (4000\ \text{lb}) = 3600\ \text{lb}$

EXAMPLE 2. A steel shaft of a motor turns in a lubricated bronze bearing. The coefficient of kinetic friction is 0.12. A V-belt exerts a downward pull of 225 lb on the bearing. The bearing also supports 12 lb of an armature's weight. Find the frictional force and the retarding frictional torque on the 0.75 in shaft. Note that even though the forces are straight downward, the shaft tends to roll up the side of the bearing before slipping begins. Wear occurs in the dashed area, 20° from bottom dead center.

SOLUTION: The normal force is given by $N = F \cos \theta$

$N = 237 \cos 20° = 223\ \text{lb}$

The frictional force tangent to the journal is:

$f = \mu N = 0.12(223\ \text{lb}) = 26.8\ \text{lb}$

The retarding torque is (Force x lever arm):

$T = f \cdot \ell = 26.8\ \text{lb} \times 0.375\ \text{in} = 10.0\ \text{in} \cdot \text{lb}$

## ROLLING FRICTION

Use of wheels, rollers, or ball bearings greatly reduces friction since, theoretically, there is no sliding friction involved. In a practical sense, however, the wheel or the surface (or both) will flatten some under the pressure of contact. A soft wheel tends to flatten on a hard surface (automobile tire for example). Consequently, a larger surface is in contact and some sliding is involved since there will be some relative motion.

A hard wheel on a soft track (wagon wheel rolling on a muddy road for example) leaves a deep track in its path. Not only is the wheel trying to roll uphill all the time trying to get up out of the track, but there is considerable sliding on the sidewalls of the wheel.

Steel rollers tend to flatten some and to sink into a steel track or raceway. Even though the effect would not be noticeable to the naked eye, nevertheless, it is present and some friction is present even in the best of ball or roller bearings.

Rolling friction is always less than sliding friction as a comparison of Table 1 and 2 shows. The formula for rolling friction is identical to that for sliding friction, but the coefficients of friction are different.

| | $\mu$ |
|---|---|
| Rubber tire on concrete | 0.04 |
| Steel ball bearings on steel | 0.0025 |
| Steel roller bearings on steel | 0.003 |

(Table 2)

ANGLE OF REPOSE

If the component of weight parallel to an incline is just equal to the frictional force, (see Fig. 5) then the object will just slide down the incline at constant speed. The net force along the incline is zero since P = f:

$$W \sin \theta_r = \mu W \cos \theta_r$$

therefore:

$$\mu = \tan \theta_r$$

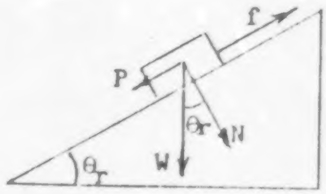


Fig 5

The coefficient of friction can be found by raising the incline until the object just slides downhill. The angle is called the angle of repose or the angle of uniform slip. As an example, kernels of grain or sand in a pile make a specific angle with the horizontal depending on the angle of repose or coefficient of friction between grains.

## PART II

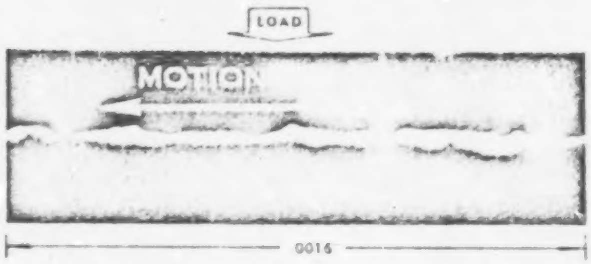
## WHAT CAUSES FRICTION?

The forces that cause a tire to flex or flatten or those that are exerted on a wheel as it tries to roll up out of an indented raceway, have components in a backward direction. This backward component is a part of rolling friction. Another part of rolling friction, however, is attributed to sliding between surfaces in relative motion. The question, then, reduces to the cause of sliding friction.

If the surfaces are rough, the object is supported on stilts, peaks or prongs that hang down from it or stick up from the surface the object slides on. As the object begins to slide, the prongs bend over. After a high point has passed by, the prong then is released, perhaps vibrates a bit as it dissapates its stored up energy. It may permanently be bent or broken off. Friction can be attributed partially to the force required to bend these microscopic prongs.

A smooth surface has fewer prongs to bend and friction is reduced by smoothing the surfaces. A strange thing about friction, however, is that friction tends to increase after reaching a certain smoothness. Why does this happen? Before that question can be answered, some other discussion is necessary.

## REAL CONTACT AREA



*Magnified profile of highly polished surfaces shows how rough an apparently smooth metal surface can be and the small areas of actual contact between them. The finish of the two surfaces represented here is 8 micro-inches R.M.S. Magnification is 2000 times.*

Figure 6 *

Figure 6 shows a highly magnified profile of very smooth surfaces. The four contact points have a real contact area that is a small fraction of the apparent area. The molecules of the upper surface are in real adhesive contact with those of the lower surface at these points. They are as close together at the four points of contact as they are inside the material of either object. Heat and electricity will conduct through these points (if the materials are good conductors). They are actually welded together at these points.

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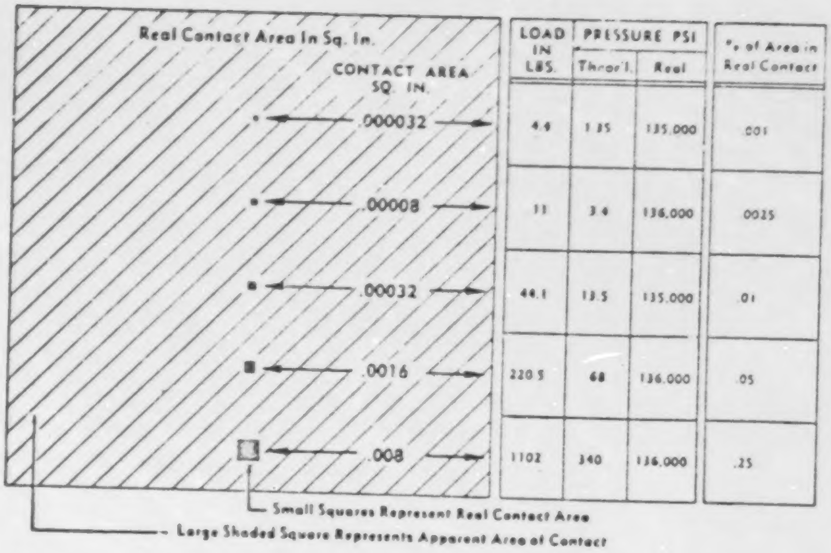
Real Contact Area In Sq. In.
CONTACT AREA SQ. IN.
.000032
.00008
.00032
.0016
.008
Small Squares Represent Real Contact Area
Large Shaded Square Represents Apparent Area of Contact

| LOAD IN LBS. | PRESSURE PSI |  | % of Area in Real Contact |
|---|---|---|---|
|  | Theor'l. | Real |  |
| 4.4 | 1.35 | 135,000 | .001 |
| 11 | 3.4 | 136,000 | .0025 |
| 44.1 | 13.5 | 135,000 | .01 |
| 220.5 | 68 | 136,000 | .05 |
| 1102 | 340 | 136,000 | .25 |

Figure 7*

*Electrical measurements of the actual contact area of two ground and lapped steel flats at various loads provides the data presented here. At each loading, true bearing pressure based on actual contact area is very high, approaching the compression yield strength of the material. It is surprisingly uniform despite the load imposed.*

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The shaded portion of Figure 7 shows the apparent area of two steel flats in contact(3.25 in$^2$). The small dark squares show the real contact area as the normal force increases. The real contact area increases from 0.000032 in$^2$ to 0.008 in$^2$ as the normal force increases from 4.4 lb to 1102 lb. The percent of area in real contact increases from 0.001% to 0.25%.

Notice in Figure 7 that the apparent (theor'l) pressure (force divided by apparent area) increases from 1.35 lb/in$^2$ to 340 lb/in$^2$. The real pressure (force divided by real area) does not change and is very high, near the yield point of the metal.

Some quick calculations show that the real contact area increases in proportion to the normal force (see Fig. 7). Friction is, therefore, proportional to the real contact area even though it is unrelated to the apparent area. Real contact area is difficult to measure; electrical resistance is inversly proportional to area, so the contact area could be measured electrically if the materials are good conductors. Perhaps it's just as well that friction is determined as a function of the normal force.

Now to explain why friction increases as the surfaces become highly polished. When a smooth object slides over another, a force must break the adhesive (or cohesive) bonds at points of real contact. At rest, the object settles down and a few more points adhere. Once in motion, there is no time for settling. With fewer points in real contact at any instant, the coefficient of kinetic friction is less that that for static friction.

Surfaces with extreme smoothness have a greater ratio of real contact area to apparent area. There are more adhesive bonds to break as motion begins, so the frictional force becomes greater as surfaces become smoother. The real contact area may become a large percentage of the apparent area. In such cases, friction may be reduced by reducing the apparent area. The bearing surface of jewelled bearings in watches is an example of such extreme smoothness.

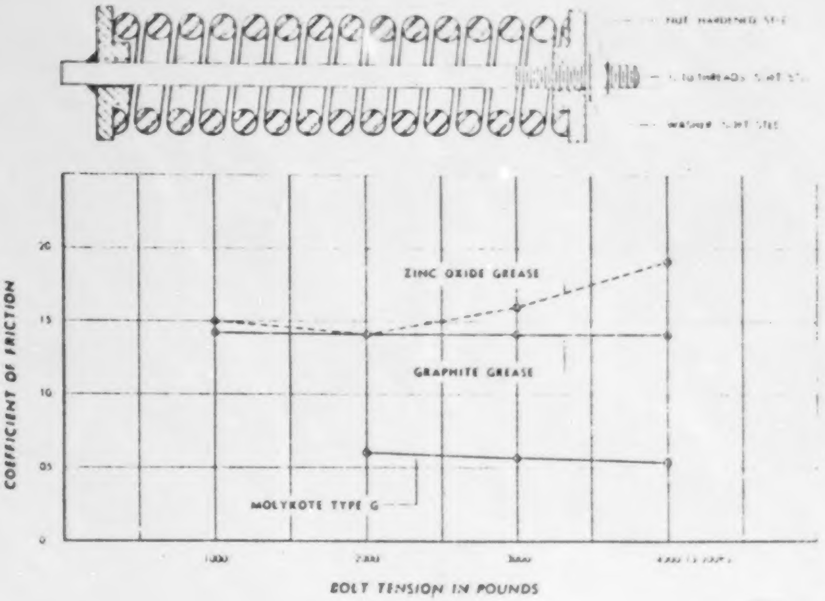

Figure 8*

*Coefficient of friction for various solid lubricants calculated from data compiled with assembly shown above graph. A calibrated torque wrench was used and spring deflected to obtain bolt tension. Values for the molybdenum disulfide lubricant below 2000 lb tension were unobtainable because the wrench did not indicate the small torque values involved.*

The coefficient of friction may change as higher pressure or higher temperatures are applied to the sliding surfaces. Figure 8 describes an experiment showing the change in the coefficient of friction as higher pressures are applied. The coefficient of friction of certain automobile tires such as "racing slicks" increases as the temperature goes up. The high sulfur content causes the tire surface to become sticky when heated. The nature of such changes is dependent on the nature of the materials themselves.

## LUBRICATION

Fluid friction is a result of frictional force when a liquid flows past a solid surface and the flow between the molecules of the liquid itself. Since the molecules of a liquid are free to move, the use of liquids between sliding surfaces prevent most of the adhesion that is the source of friction. Fluid friction is much less pronounced than friction between solids (see Table 1). Naturally, there are great differences in lubricants.

Additional information and problem examples may be found in your text.

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PROBLEMS

Module M 6 FRICTION

1. Explain the difference between real contact area and apparent area between sliding surfaces and the effect of each on friction.

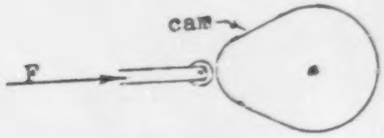
2. Explain the difference among static friction, limiting friction, and kinetic friction between sliding surfaces.

3. Explain how the angle of repose can be used to find the coefficient of friction between sliding surfaces.

4. Explain how the normal force acting on sliding surfaces on an incline changes as the angle of incline changes from 0° to 90°. Show a graph of this relationship.

5. A shop cart has large wheels which have a coefficient of friction of 0.06 including bearing friction. A 105 lb molding rests at the center of the 75 lb cart. What force is required to move the cart? Is it necessary to calculate the friction on each wheel?

6. Cams are used to operate switches and various transfer mechanisms. The force on the roller (see diagram) that rides on a cam varies from 2.8 lb to 5.1 lb due to spring tension. If the coefficient of friction is 0.06, what is the minimum and maximum frictional force on that particular cam? Assume the force is normal to the cam surface.



7. A steel armature shaft rotating in a motor turns in a lubricated bronze bushing. The coefficient of friction is 0.10. A V-belt exerts an upward pull of 195 lb on the bushing. The bushing also supports 11 lb of the armature's weight. Find the frictional force on the shaft if it rolls 15° from top dead center before spinning begins. See figure 4 in the information sheets. Assume V-belt tension doesn't increase when the shaft rolls.

8. A delivery truck pulling a trailer with a load of metal on it is climbing a hill with a 12° incline. If the trailer and load weigh 5 ton, and the coefficient of rolling friction is 0.06, find the force of friction on the trailer and the pull the truck must exert to maintain constant speed up the hill. Neglect air resistance.

9. Hydraulic castings in a manufacturing plant slide down an incline on the assembly line. If the angle is 28°, what is the coefficient of friction? If the coefficient of friction was 0.62, what would be the angle of incline?

PROBLEMS CONTINUED

10. In tightening a bolt, sliding occurs between the threads and between the head of the bolt and the washer. Correct tension, if it is required, is achieved with a torque wrench. If the tension in a ½ in bolt is 1000 lb, what is the friction (limiting) if the coefficient is 0.75? What happens to the tension and friction as the bolt is tightened?

11. A screw jack is used to lift a 1200 lb weight vertically. If the limiting coefficient of friction is 0.68, find the limiting frictional force between the threads of the screw.

12. A disk is rigidly attached to an axle. Brake shoes press against each side of the disk. A 1700 N frictional force will prevent the axle from rotating. Will a force of 1960 N on the shoes hold the axles if the limiting coefficient of friction is 0.4?

ANSWER KEY (PROBLEMS)

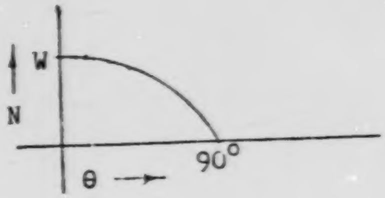
Module M 6 FRICTION

1. See information sheet. Friction is independent of the apparent area.

2. Static friction varies from zero to the limiting friction depending on the applied force. Kinetic friction is the average value after motion begins.

3. Raise incline until slippage begins, note angle: $\mu = \tan \theta r$.

4. $N = W \cos \theta$



5. 10.8 lb, no

6. 0.17 lb, 0.31 lb

7. 19.9 lb

8. 587 lb, 2670 lb

9. 0.53, 31.8°

10. 750 lb, both increase

11. 816 lb

12. No, 784 lb on one shoe, 1568 lb on disk.

EXPERIMENTS

Module M 6 FRICTION

PURPOSE: The pupose of this experiment is to study friction and some of the factors that influence friction. Friction on an inclined plane is also studied.

CAUTIONS:

1. Read all the instructions before handling any of the equipment.
2. Keep the plastic foam keeper in place on the Harvard trip balance when it is not being used.
3. The balance scale is a delicate instrument. When you weigh the wooden block, take it to the balance scale instead of carrying the balance scale to your lab station. It receives less wear and tear this way.
4. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
5. Observe all cautions listed in the procedure section below.

EQUIPMENT: Check to see if all the following equipment is available before you start. Ask your instructor if you have any questions about the equipment.

1. Inclined Plane (Sargent-Welch #0809)
2. Friction Block (Sargent-Welch #0977)
3. String
4. Weight hanger
5. Slotted weight set
6. Balance scale and weights available in classroom.

INFORMATION: Friction always opposes motion or the tendency of motion. On an incline, friction is a force downward when an object is being pulled up the incline. When the object moves down the incline, friction is upward along the incline.

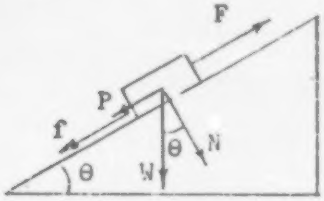


Fig 1

Figure 1 shows the first case where a force (F) pulls the object upward. It must overcome the effects of force P (component of the weight down the incline, $P = W \sin \theta$) and friction (f). Figure 2 shows an object moving down the incline. Notice that friction is upward in this case. The object will move only if P is larger than f.

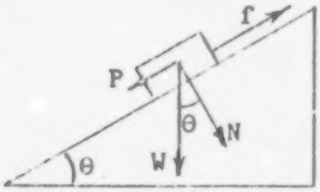


Fig 2

The frictional force (f) is equal to the normal force (N) (the perpendicular component of the weight) times the coefficient of friction ($\mu$).

$$f = \mu N$$

The normal force can be found by the formula: $N = W \cos \theta$.

For further information, see your text or the information sheet in this booklet.

PROCEDURE:

1. Place the inclined plane (set on 0°) on a table or lab bench so the pulley hangs over the edge.

NOTE: Exact leveling of the surface is unnecessary.

2. Weigh the friction block on the balance scale. Record on the data sheet.

3. Attach the wooden friction block to one end of the string on the hook provided and attach the other end of the string to the weight hanger.

4. Place the block on the surface of the inclined plane near the center and let the weight hanger hang over the edge of the table with the string in the pulley.

NOTE: The string between the friction block and the pulley should be parallel to the plane. Adjust by raising or lowering the pulley.

5. Hang slotted weights on the hanger to find the force required to just move the friction block along the plane. Be sure to include the weight of the hanger (50 g). The weight on the hanger and the hanger itself is equal to the frictional force on the block. Record on the data sheet.

NOTE: The block should just creep when you tap the inclined plane surface lightly with your fingernail or pencil.

6. Add 200 g to the weight of the block by laying slotted weights on top.

7. Repeat step 5 after resetting the block in the same place on the incline. The block should creep at about the same rate with the same amount of tapping. Record the data.

8. Repeat steps 6 and 7 with 400 g, 600 g, and 800 g on the block. Record the data.

9. Calculate the coefficient of friction for each line, record in the proper place and find the average.

10. Raise the incline to find the angle of repose. The block without weights should just creep down the incline by tapping as before. Record the angle, calculate the coefficient of friction and compare with step 9 by calculating the percentage difference.

11. Set the angle of the incline between 25° and 35°. Record.

12. Calculate the force (F) required to just make the block creep up the incline. Refer to Figure 1 and the information that accompanies it. (Page 17) Record.

13. Measure the force (F) required to just make the block creep (by tapping) up the incline.

14. Compare the calculated and measured value of the force F. (Find the percentage difference.)

15. Calculate the percentage ratio of the area of the block along the edge to the area of the block laying flat.

16. Adjust the angle of incline to 0°, lay the block on edge and adjust string so it is parallel to the plane. Measure the force of friction by hanging slotted weights on the hanger.

17. Compare the frictional force measured on edge to that measured in step 5 by calculating the percentage ratio.

18. The results of step 15 and 16 should show that friction is independent of the apparent area, even though friction may be slightly different. What do you attribute the difference to?

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus
Milford, Nebr. 68405

Module: M 7

Title: The Laws of Motion

Module Contents:
1. Force causes change in motion
2. Inertia
3. Newton's three laws of motion
4. Mass and weight units

Program: This module has been especially prepared for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology
5. Electromechanical Technology

Purpose: The purpose of this module is to extend the study of motion (module M 5) to include the cause of changes in motion. It is the change in motion and the forces involved that you as a technician must understand and control if you want matter to interact to your advantage. Applications are included in the problem sets and are much the same as those in module M 5. The study of Newton's laws of motion is prerequisite for modules on work, energy, power, and others that follow.

Producer: Gene Waring

Date Produced: September, 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## Module M 7 THE LAWS OF MOTION

## OBJECTIVES

When you have satisfactorily completed this unit, you will be able to:

1. Define inertia.
2. State Newton's three laws of motion.
3. Distinguish between mass and weight by defining each, by stating the units of each in the British, SI and cgs measuring systems and by stating the relationship between the two quantities.
4. State the difference between absolute and gravitational measuring systems.
5. Show an understanding of Newton's third law by citing several examples of action-reaction pairs of forces applied to various pairs of objects.
6. Show that any pair of action-reaction forces do not cancel by describing a pair of objects, the direction of the forces on them and which object each force acts on.
7. Solve various problems involving Newton's second law.
8. Solve various problems involving Newton's second law and the laws of motion described in module M 5.
9. Carry all units and dimensions through the entire solution of problems.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of motion. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The results of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions, correctly. The answer key page (pink paper, page 7 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 5 ).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc. that the objectives refer to. This list will be very useful as an aid to learning them.

A. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 3, section 3.16-3.22, pages 66-83.

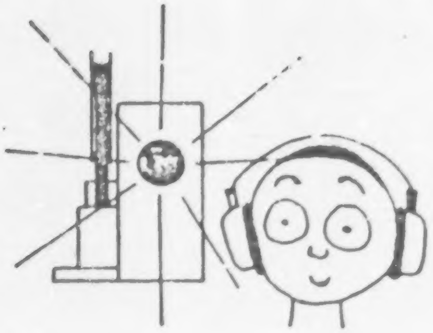
B. Elements of Physics, Smith A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 6, sections 6.1-6.8, pages 63-71. Omit section 6.9.

C. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 6, sections 6.1-6.7, pages 54-67. Omit section 6.8.

D. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 4, sections 4.1-4.6, pages 43-55. Omit section 4.7.

E. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 5, sections 5.1-5.8, pages 62-77.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Newton's Laws of Motion, (BFA Ealing 80-4187)

B. Inertia I, (BFA Ealing ISBN 0-03-080162)

C. Inertia II, (BFA-Ealing ISBN 0-03-080163)

D. Newton's First and Second Laws, (BFA Ealing 80-2736)

E. Newton's Third Law, (BFA Ealing 80-2744)

F. Inertial Forces, (BFA Ealing 80-2132)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page 8 ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving Newton's Law problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are two experiments in this module. They will give you experience involving the laws of motion.

Read the laboratory instructions in this booklet (yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M-7) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

## Module M 7 THE LAWS OF MOTION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The inertia of an automobile increases as its velocity increases.

T - F 2. According to Newton's third law, a single externally applied force cannot act on an object.

T - F 3. The kilogram is the unit of mass in the MKS (SI) measuring system.

T - F 4. The slug has units that may be expressed as lb/ft·s in British fundamental units (F = ma).

T - F 5. A net force of 5 lb acting on a 1.25 slug mass will accelerate at 4 ft/s$^2$.

6. A weight of a large torque wrench is 7 lb. Its mass in slugs is:

a) 0.22 c) 0.71
b) 224 d) cannot be calculated

7. A certain net force gives an 8 kg lead ball an acceleration of 3 m/s$^2$. The same net force would give a 24 kg ball an acceleration in m/s$^2$ of:

a) 24 c) 12
b) 1 d) 48

8. When an object is accelerated, you know for sure that:

a) its velocity increases c) a net force acts on it
b) its velocity decreases d) it falls freely

9. A 3600 lb automobile is traveling 45 mi/h. How much distance will it take to come to a stop if a braking force of 875 lb is applied?

10. An elevator with its load weighs 5000 lb. What is the maximum upward acceleration it can have if the supporting cables can safely withstand no more than 7500 lb of tension?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 7 THE LAWS OF MOTION

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. F | I. Reading or V. Experiment 2 |
| 2. F | I. Reading |
| 3. T | I. Reading or II. Listening/Viewing |
| 4. F | I. Reading or III. Solving Problems |
| 5. T | III. Solving Problems |
| 6. a | III. Solving Problems |
| 7. b | III. Solving Problems or V. Experiment 1 |
| 8. c | I. Reading |
| 9. 280 ft | III. Solving Problems or V. Experiments |
| 10. 16 ft/s$^2$ | III. Solving Problems or V. Experiments |

PROBLEMS

## Module M 7 THE LAWS OF MOTION

1. Compare an action-reaction pair of forces with a resultant-equilibrant pair. Both pairs are equal and opposite. The latter pair cancels. Why doesn't an action-reaction pair cancel?

2. Whiplash is a serious neck injury incurred by a driver or passenger in a stopped car which is struck from behind. What causes such injuries?

3. If a force which is equal to the weight of an object is applied to the object, what will be the acceleration?

4. Express the units of mass in fundamental British units.

5. Express the units of force in fundamental MKS and cgs units.

6. What happens to a person standing on a bus or sitting in a car when (a) there is a large forward acceleration, and (b) when the brakes are suddenly applied?

7. Discuss the physics involved in each of the following:

   a) Removing mud or snow from boots by kicking against a rock.
   b) Removing water droplets from hands by the whipping action of your wrists.
   c) Forcing a hammer head onto a handle by jamming the handle against a concrete step.
   d) Running up to a patch of ice then sliding.

8. An electric hoist momentarily accelerates a load of metal at 3 m/s$^2$. If the load has a mass of 2000 kg, what is the net force on it?

9. A truck pulls a 2500 lb trailer with a portable generator for a welder on it. If the net force on the trailer is 275 lb, what is its acceleration?

10. A machinist carrying a 45 lb tool box enters an elevator. The elevator car accelerates and decelerates at 8.3 ft/s$^2$. What force will he have to apply to support the tool box as the elevator starts upward? As the elevator moves upward at constant speed of 6 ft/s? As the elevator stops at the 5th floor?

11. A welder, returning to the shop from a job, was traveling 55 mi/h in a 4600 lb pickup. As he came to a railroad crossing, he noticed a train approaching. He applied the brakes at a point 420 ft from the crossing. If the braking force (assumed constant) was 1170 lb, was he able to avoid collision?

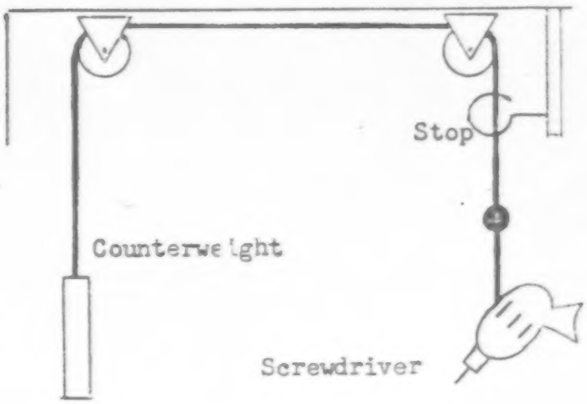
12. A welder accidentally drops a 1 lb clamp from a 40 ft tower. A 6 ft tall construction worker (not obeying all safety rules) was standing underneath. The clamp made a dent in the worker's metal hard hat, forced the hat downward on his head, and caused his head to move downward slightly. What average force was exerted if the clamp came momentarily to a stop in a total distance of 2.5 in before falling away?

13. A 2070 kg load of iron is being lowered by a crane. A maximum braking force of 3500 N can be applied by the operator. What minimum distance is required to stop the load if it is being lowered at a speed of 1 m/s?

14. A trailer and its load (portable welder and generator) weighing 5000 lb, is being pulled by a truck. As the truck begins to move, it accelerates at 3.4 ft/s$^2$. What force does the truck exert on the trailer hitch if the coefficient of friction between the trailer's tires and road is 0.06?

15. A crane is used to lift a 2070 lb lathe onto a truck bed. As the lathe begins to clear the ground, the total tension in the cable is 2185 lb. What is the acceleration at that instant?

16.



At one station on a manufacturing assembly line, a pneumatic screwdriver is used to tighten screws on a hydraulic pum

The screwdriver is attached to a small cable that runs over a set of pulleys to a counterweight in a remote corner (see diagram). The tool is up out of the way when not in use. The counterweight weighs 5 lb, the screwdriver is 3 lb, and there is 1.25 lb of friction in the pulley. Find the acceleration of the screwdriver-counterweight system, neglecting the weight of the cable. The tool is restricted from moving more than 3 ft upward. How much time is required for it to move that distance after being released? With what speed does it strike the restriction?

17. A dowel pin is being driven into a die component. The hammer has a mass of 0.35 kg and is moving at a speed of 4.5 m/s just before contact with the pin. Assuming the acceleration is constant, find the average force exerted on the hammer if it comes to a stop while driving the pin 1 cm. What is the force on the pin?

18. Answer the same question as in problem 17; if the hammer (more realistically) rebounds with a speed (just after contact is broken) of 3 m/s.

ANSWER KEYS (PROBLEMS)

Module M 7 THE LAWS OF MOTION

1. Resultant and equilibrant act on same object, action-reaction don't.
2. Neck, bones, and muscles cannot exert necessary force to accelerate head. Inertia causes head to be left behind; twisting neck, causing injury.
3. 32 $ft/s^2$
4. $lb \cdot s^2/ft$
5. $kg \cdot m/s^2$, $g \cdot cm/s^2$
6. See definition of inertia.
7. Boot, hand, and hammer handle suddenly stop; but, mud, snow, droplets, and hammer head keep going. Inertia causes objects to continue moving.
8. 6000 N
9. 3.52 $ft/s^2$
10. 56.8 lb, 45 lb, 33.3 lb
11. Yes, stopped in 400 ft.
12. 163 lb
13. 30 cm
14. 831 lb
15. 1.78 $ft/s^2$
16. 3 $ft/s^2$, 1.4 s, 4.2 ft/s
17. -373 N, + 373 N, NOTE: Force and acceleration are not constant.
18. -320 N, + 320 N, NOTE: Force and acceleration are not constant.

EXPERIMENTS

## Module M 7 THE LAWS OF MOTION

PURPOSE: The purpose of these experiments is to (1) to study Newton's Second Law of Motion on an air track. You will make these runs with the spark recorder; (2) to use an inertial balance to see that mass can be measured independently of the force of gravity.

CAUTIONS:

1. Read all of the instructions before handling any of the equipment.
2. The Basic Spark Source can cause deep painful burns as well as shock. Read and follow the instructions carefully.
3. Observe all cautions in the procedure section of these instructions.
4. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.

## EXPERIMENT I

INFORMATION: A linear air track is used in the first experiment. It is a simple device which allows you to observe motion in which there is almost negligible friction. Glides are supported so they "float" and move on a cushion of air produced by blowing air with a vacuum cleaner out of small holes on the track. The viscosity of the thin layer of air between the glider and track is the only source of friction

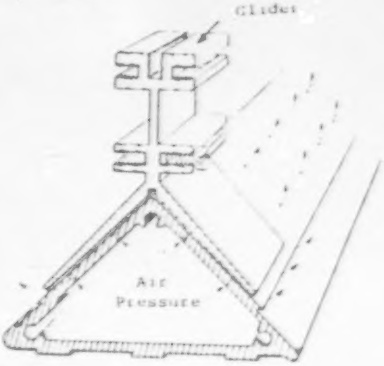


Figure 1. Track Cross Section
By permission: The Ealing Corporation

The air track is a precision device. Distances along the track can be measured to the nearest millimeter. The timing measurements needed for studying motion are made with a timing device that generates high voltage pulses at regular intervals. The resulting spark holes recorded on spark paper make a record of the position of the glides each time without affecting the motion of the glider. You should view film A, (See Listening/Viewing, page 4 ) before proceeding with the experiment.

EQUIPMENT:

1. Student 1.2 m air track (Ealing 33-1512)
2. Two stage blower - 115 v (Ealing 33-0167)
3. Various blower hoses, couplings, tees, manifolds, etc.
4. Basic spark source - 60 Hz (Ealing 33-2403)
5. Spark tape (Ealing 33-0274)

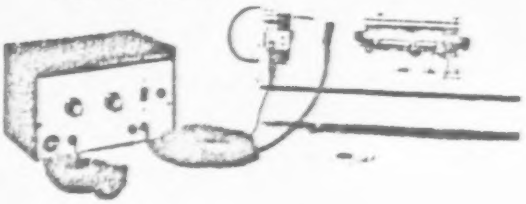


Figure 2. Basic Spark Source
By permission: The Ealing Corporation

Check to see that all equipment is available before you start. Ask your instructor if you have any questions about the equipment. Obtain a data sheet from the instructor.

PROCEDURE:

CAUTION: Do not plug in the basic spark sourc until you are ready to use it. See step 14 below. Shocks from this spark source can burn small, deep, and very painful holes in your skin. Other injuries can occur as you react to the shock. BE EXTREMELY CAREFUL NOT TO TOUCH THE SPARKING WIRE when the spark source is attached.

CAUTION: Be careful not to drop the glides. Dropping them from even a few inches height will probably ruin them. To avoid damaging surfaces, do not slide the glides on the track with the air supply shut off.

1. Attach the air hose from the vacuum cleaner to the air track.

CAUTION: Keep the air hose on the back or side of the table so it will not be bumped. It could drag the air track off the table.

2. Plug in the air supply (vacuum cleaner) and turn it on. If only one track is being used, remove one rubber stopper from the manifold on top of the air supply. The entire supply is not needed for one track.

LEVEL THE AIR TRACK

3. Remove all gliders except one. Place one glider near the center of the track. If the track is level, the glider will not accelerate in either direction. Turn the adjusting screw knob on the air supply end of the track. Note: Slight adjustments make large changes in the glider's motion.

CAUTION: Do not bump or jar the track once it is leveled. Small irregularities in the table top will have a large effect on the gliders motion if the track is moved. Naturally, you should also avoid bumping or jarring the table for the same reason.

4. Shut off the blower during set-up time.

5. Insert a strip of spark paper in the groove on the back side of the air track. A 120 cm length is sufficient.

6. If a transfer wire is not attached to the nylon post on one end of the gliders, wrap one turn of copper wire around the post and tighten. Bend the wire in the shape shown in Figure 3.

   NOTE: The transfer wire is vertical, near the sparking wire so it will not matter if the sparking wire sags a little. The bottom end of the transfer wire is placed near the upper edge of the spark paper. By bending the wire downward, more than one run can be made on one strip of paper.

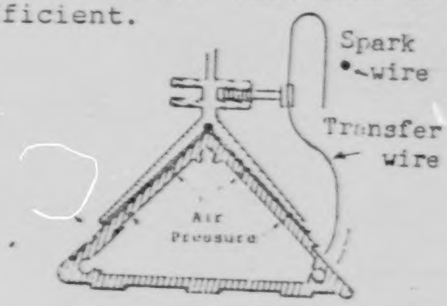


Figure 3. The Transfer Wire
By permission: The Ealing Corporation

7. Turn the blower on and move the glider slowly along the track. Check to see that the transfer wire does not touch the sparking wire or the spark paper. The gaps at both places should be as small as you can make them without rubbing. The sum of the two gaps whould not exceed 1 cm anywhere along the track. Rubbing at either place will alter the motion of the glider.

8. Use a small piece of adhesive tape to attach a strip of magnetic recording tape to the small glider. The recording tape should be attached at the same level as the upper surface of the air pulley (see Figure 4 ). The magnetic tape will then be parallel to the air track so a direct pull results.

9. Run the magnetic tape over the air pulley (see Figure 4 ).

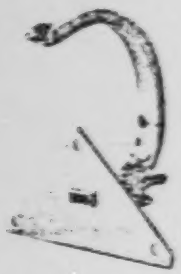


Figure 4. The Air Pulley
By permission: The Ealing Corporation

10. Attach a 10 g slotted weight to the loose end of the magnetic tape with another small piece of adhesive tape.

11. Adjust the air supply to the pulley by turning the wing screw. NOTE: Too little air will cause the tape to touch the pulley; too much will cause it to fly off and the weight will fall to the floor.

12. You are now ready to attach the Basic Spark Source. USE CARE! OBSERVE ALL CAUTIONS.

13. Attach the alligator clip leads to the air track (see Figure 2)
    a) Attach the large wire (hot) with the red lead to the sparking wire near the rubber band launcher.
    b) Attach the small wire (ground) with the black lead to the end stop near the rubber band launcher.

14. Set the Timing Source Selector on the 10.0 Hz position. Note that the sparks will occur 0.1 s apart.

15. You may now plug in the Basic Spark Source but observe the following cautions:

CAUTIONS

1. Use the spark source only when recording. Do not fire it longer than necessary.
2. Never push the remote operate button without insuring a proper gap; in such a case, the discharge energy will occur internally. Continued operation without a proper gap (See Step 10) will damage the electronic components within the unit.
3. Unplug all spark sources when making lead changes; BE SAFE, assume the unit will misfire.

16. You are now ready to make your first recording:
    a) Push the glider back so the spring bumper just touches the bumper on the end stop.
    b) Simultaneously, release the glider and depress the remote operate button on the spark source
    c) Be sure to turn off (release) the remote operate button as soon as the glider reaches the opposite end of the track to avoid making spark holes on the return trip and confusing the record.

17. Unplug the spark source. BE SAFE!

18. Remove the small glider and replace it with a large one.

19. Adjust the spark transfer wire so it will record near the center of the spark paper (see steps 6 and 7).

20. Make your second recording (repeat steps 15 and 16).

21. Unplug the spark source. SAFETY FIRST!

22. Add another 10 g slotted weight to the free end with adhesive tape.

23. Adjust the spark transfer wire so it will record near the bottom edge of the spark paper (see steps 6 and 7).

24. Make your third recording (repeat steps 15 and 16).

25. You now have three records on spark paper. Unplug the equipment and put it away.

26. Tape the spark paper to a table and lay a meter-stick on it edgewise so the markings are adjacent to the spark holes. Do not place the end of the meter-stick on the first hole. Instead, put the one centimeter mark on the first hole and subtract it from all successive readings. Ignore the spark holes made when the bumpers were still in contact during launch.

27. Record the position of the holes for each of the three spark records in the proper place on the data sheet.

28. Calculate the average velocity for each interval for each spark record. The average velocity for a given interval is the instantaneous velocity at the mid-point of the interval.

29. Calculate the acceleration from the mid-point of one interval to the mid-point of the next interval for each successive interval. Record in the table: $a = (v - v_0)/t$

30. Average the accelerations you have listed in the tables for each spark record.

31. If the accelerating force is the same on two different objects, the acceleration ratio should equal the inverse of the mass ratio:

$$\frac{a_1}{a_2} = \frac{m_2}{m_1}$$

Weigh the masses on a balance scale and add the mass of the slotted weights. Neglect the mass of the magnetic tape. Compare the acceleration ratio (first and second spark records) and the mass ratio by finding the difference divided by the mass ratio. What factors cause the small difference?

32. Calculate the force ratio and the acceleration ratio (second and third spark records). These ratios should be equal. Compare by finding the difference divided by the force ratio. What factors cause the small difference?

## EXPERIMENT 2

INFORMATION: Inertia is the property of matter that causes (1) a body at rest to remain at rest, or (2) a body in motion to remain in motion at constant velocity unless acted upon by an externally applied force. Newton's first law states that all matter has inertia. When you measure the mass of an object, you are measuring its inertia. A body of large mass has a large amount of inertia; a body of smaller mass has less inertia.

Weight is the pull of gravity on an object and is proportional to its mass. An object with a large mass will weigh a large amount; a small mass will weigh less.

EQUIPMENT:

1. Inertial balance (Sargent-Welch Cat.#0875)
2. Six 100 g slotted masses
3. One 3 in. C-clamp
4. One stop clock
5. Harvard trip balance
6. Various support rods and clamps

Check to see that all equipment listed is available. Obtain a data sheet from the instructor.

### PROCEDURE

1. Securely clamp the inertial balance to a laboratory bench using the C-clamp. See figure 5.

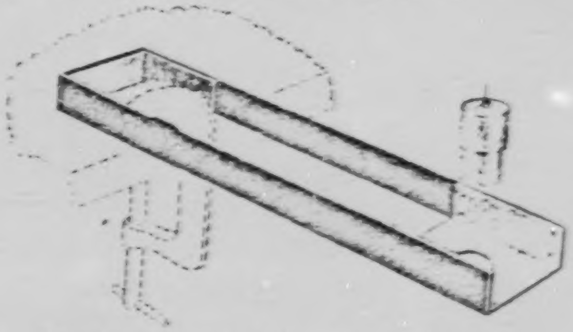


Figure 5. The Inertial Balance
By permission: The Sargent-Welch Scientific Co.

2. Plug the stop clock into a wall socket. Test the remote operating switch. NOTE: The clock is decimalized; each revolution of the large hand is ten seconds.

3. Place a 100 g mass in the center of the balance pan.

4. Deflect the balance pan about 3/8 to ½ in to one side by finger pressure. Release the balance so it oscillates freely.

5. After several oscillations, (when the mass stops moving on the pan) measure the time for fifty complete cycles.

   NOTE: Start the clock at one end of the swing; count "zero" at the same instant you start the clock.

   NOTE: Be sure to count complete cycles. One complete cycle is a swing over then back to the starting point.

6. Record the time for fifty cycles on the data sheet.

7. Repeat steps 4, 5 and 6, with 200 g, 300 g, 400 g, 500 g, and 600 g on the balance pan.

8. Calculate the frequency, period and square of the period for each trial and record on the data sheet.

9. On the graph paper provided, plot the mass horizontally and the period and the square of the period vertically. Which curve shows a linear relationship? Which variable is mass proportional to?

10. Remove the slotted masses from the pan and place the unknown mass through the hole in the balance pan. It should rest on the collar formed by the larger diameter.

11. Repeat steps 4, 5, and 6 with the unknown mass.

12. Determine the mass of the unknown by plotting the square of the period on the graph.

13. Assemble the stand, rod, clamp, and string as shown in figure 6. Suspend the unknown mass so the collar is not resting on the balance pan.

14. Repeat step 4, 5 and 6 with the unknown mass suspended.

15. Determine the mass as in step 12 and compare. Does the pull of gravity have a significant effect on the mass of the unknown?

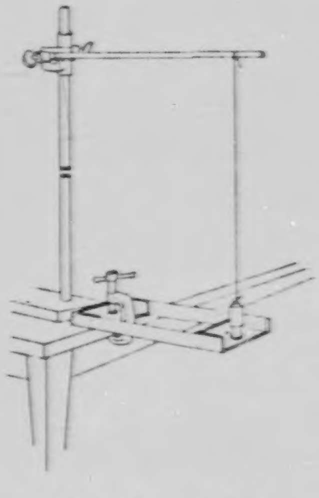


Figure 6. The Unknown Mass
By permission: The Sargent-Welch Scientific Company

16. Measure the mass of the unkown using the Harvard trip balance.

17. Calculate the percentage difference in the graph value of the unknown mass and that measured on the Havard trip balance.

18. Dismantle the equipment and put it away.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus
Milford, Nebr. 68405

Module: M 8

Title: ENERGY & POWER

Module Contents:

1. Work, energy, and power
2. Classification of energy
3. Units of work, energy, and power
4. Energy transformation and the work equation
5. The law of conservation of energy

Program: This module has been prepared especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to study the principles of work and energy. Interactions of objects have previously been studied in terms of forces and acceleration which are vector quantities. The same interactions can be studied more easily, however, with the use of the scalars: work, energy and power. The law of conservation of energy unifies and simplifies the description of motion. Practical examples are included. This module is a prerequisite for modules on simple machines, power measurement, and others.

Producer: Gene Waring

Date Produced: October, 1976

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STUDENT INSTRUCTION

Module M 8 ENERGY & POWER

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define work, energy, and power.
2. State the derived units of work, energy, and power in the MKS, cgs, and British systems and convert one to the other.
3. Define kinetic energy, elastic potential energy and gravitational potential energy.
4. State the formulas for kinetic elastic potential and gravitatational potential energy, for work, for power and for Hooke's law for springs.
5. Solve various problems in which the formulas in objective 4 are involved.
6. Cite several examples of one form of energy in the process of being transformed to other forms.
7. State the law of conservation of energy and the work equation, and solve various problems involving these principles.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of energy and power. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 7 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 8 ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read Chapter 4, sections 4.1-4.6, pages 84-94, and section 4.11, pages 103-106, and Chapter 10, section 10.5, pages 247-248.

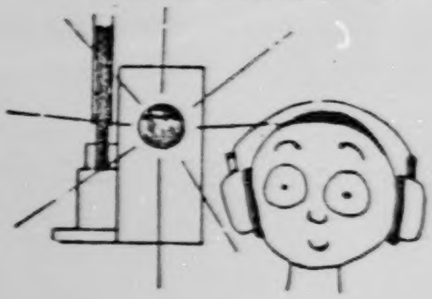
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read part of Chapter 7, sections 7.1 to 7.7, pages 77-85 (omit section 7.8, 7.9, and 7.10).

D. Physics for Career Education, Ewen, D , Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of Chapter 9, sections 9.1-9.3, pages 103-116.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 8, pages 91-107 (you may omit page 97).

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc 1st ed., 1966. Read Chapter 9, pages 123-141 (omit section 9-4).

II. Listening/Viewing: The following single concept film loops (8 mm are available in the Learning Resourc Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702 and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Gravitational Potential Energy, (BFA Ealing 80-3817) QC/122/P94x/#8

B. Kinetic Energy, (BFA Ealing 80-3825) QC/122/P94x/#11

C. Conservation of Energy-Pole Vault, (BFA Ealing 80-3833) QC/122/P94x #3

D. Conservation of Energy-Aircraft Takeoff, (BFA Ealing 80-3841) QC/122/P94x/#2

E. Conservation of Energy, (BFA Ealing 80-276) QC/122/M462x/#2

F. A Method of Measuring Energy-Nails Driven into Wood, (BFA Ealing 80-3791) QC/122/P94x/#12

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page ). Answers are given for each problem. Solve as many of them as you feel are necesaary to gain competence in solving work and energy problems. The problems from number six on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about work, energy and power.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M-8) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module M 8 ENERGY & POWER

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Work will always be done on an object if an external force acts on it.

T - F 2. A pair of automobiles of equal mass and equal speed, but going in opposite directions have a net kinetic energy of zero.

T - F 3. One joule equals one newton-meter.

T - F 4. In lifting a TV set from the floor to a table, the work done is: the weight of the set times the height of the table.

T - F 5. Energy can be created only in machinery classified as engines, motors, generators and furnaces.

6. The unit of energy expressed in fundamental MKS units is:

a) kg·m
b) ft·lb
c) $kg\ m^2/s^2$
d) $kg\ s^2/m^2$

7. A 64 lb weight is lifted 20 ft. The work done is:

a) 1280 J
b) 41 000 ft·lb
c) 12 800 erg
d) 1280 ft·lb

8. A 4000 lb automobile is traveling 45 mi/h (66 ft/s). What is its kinetic energy?

a) 272 000 ft·lb
b) 272 ft·lb
c) 272 000 watts
d) 8 710 000 ft·lb

9. A spring has a force constant of 3.6 lb/ft. A force of 5 oz will stretch it:

a) 0.087 in
b) 1.04 in
c) 1.39 ft
d) 0.72 ft

10. What average force would be acting on a 25 g bullet as it penetrates wood to a depth of 15 cm? Its speed just before impact is 260 m/s.

11. An elevator and its contents weigh 3 ton. It moves 300 ft to the top of a mine shaft in 50 s. What power is required?

## ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 8 ENERGY & POWER

| Question-Answer | | If you missed this question, you are directed to these learning activities: |
|---|---|---|
| 1. | F | I. Reading |
| 2. | F | I. Reading |
| 3. | T | I. Reading |
| 4. | T | I. Reading |
| 5. | F | I. Reading |
| 6. | c | I. Reading, or III. Solving Problems |
| 7. | d | III. Solving Problems, II. Listening/Viewing, or V. Experiment |
| 8. | a | III. Solving Problems, II. Listening/Viewing, or V. Experiment |
| 9. | b | III. Solving Problems, II. Listening/Viewing, or V. Experiment |
| 10. | 5630 N | III. Solving Problems, or II. Listening/Viewing |
| 11. | 65.6 hp | III. Solving Problems |

INFORMATION SHEET

Module M 8 ENERGY & POWER

## WORK

Inertia is the property of matter by which an object resists changes in its motion. An object in a friction free environment requires no forces to keep moving or to keep from moving. Objects that cannot readily be moved such as those with large inertia, or those that are bolted, rooted or cemented down, require extremely large forces to cause movement.

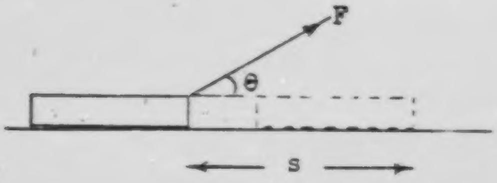
No changes are occuring in the case of objects moving without external forces or in the case of objects with external forces but no movement. Nothing is being accomplished. No work is being done. In both cases either force or movement is lacking.

Work is defined as the product of the force and the distance moved:

$$W_k = Fs$$

More exactly; work in the product of the component of the force in the direction of motion and the distance moved, or:

$$W_k = Fs \cos \theta$$



Where θ is the angle between the direction of the force and the direction of motion.

In the two cases cited above, either F or s is zero, so no work is done.

A third case in which no work is done is when the cos θ is zero. This happens when θ is 90°, when the direction of F is perpendicular to the direction of s (uniform circular motion).

Work is done on an object, however, when none of the three quantities (F, s, and cos θ) is zero. A second object must be involved in order to exert the force according to Newton's third law (action-reaction). In order for the second object to exert the force and cause movement or, in other words, to do work on the first object, it must possess an ability or a capacity to do work. It must possess energy.

## ENERGY

Energy is the ability of an object to do work. The object has the energy stored within it. Energy can be stored in one of several different forms:

1. Chemical: gasoline, coal, electrolytes, food, animals
2. Electical potential: electric or magnetic fields
3. Gravitational potential: snow in the mountains, or water behind dams
4. Kinetic: flywheels, wind, ocean streams, tides, moving objects
5. Elastic potential: springs, torsion bars
6. Heat: heat bins, steam, hot water heaters
7. Nuclear: Uranium, Plutonium, Hydrogen

The energy in most of these forms can be bought or sold by individuals, by large corporations, or by power companies. We buy gasoline and batteries to operate our car, and food to keep out bodies operating. When we employ someone for physical labor, we buy the chemical energy stored in their bodies.

Power companies buy coal, natural gas, propane, or diesel fuel to operate their generators and resell the energy in a different form.

Energy can be transported by several methods:

1. Conduction. This is the movement of energy through a material without actual transfer of the material. Heat, sound, and electrical energy are easily transported this way. Current in power lines is one example where large amounts of energy are transported by conduction.

2. Natural convection. This is the movement of the material that contains the energy. Hot air rises, water flows downhill in open streams. Ocean currents, and air currents are other examples of natural convection of energy.

3. Forced convection. This is the movement of the material that contains the energy when the movement is forced. Trains move coal, pipelines move natural gas, trucks move gasoline, pumps move water uphill, and fans move air. These are examples of forced convection.

4. Radiation. This is the movement of the energy through space without the aid of any material. Radio waves move from transmitter to receiver for example. Naturally, the energy is emitted by one object and will eventually be absorbed by another object, but matter always slows down or hinders the process when the transfer is by radiation. Energy transferred this way is in a form of electromagnetic radiation such as: radio waves, light, x-rays, and a number of others.

Energy can be stored by storing the material that contains the energy. We transfer energy usually by transferring the material. We do all these things with energy (buy, sell, move, and store it) without ever really knowing what it is. A mountain of coal or huge tanks of oil are quite obvious, but the energy they contain is not. It is only when the energy is being transformed or dissapated (used) that its presence becomes known or felt.

Individuals seldom see energy being gobbled up very rapidly. We wind a watch and see the energy stored in the spring being "used" very slowly. We see electric motors driving a fan. Modern automobiles and roads allow us to move so smoothly we are unaware of the energy involved except when a collision occurs.

We may shy away when we feel the ground shaking as a huge freight train moves by at 70 mi/h. We may be a bit nervous from the vibrations we feel down in the turbine room of a large hydroelectric plant. At 50 yards, we may have to turn our face away from the heat emitted from a red hot pig of iron in a steel factory. Volcanoes, tornadoes, and floods as well as nuclear bombs make us feel very puny indeed.

Since we can buy, sell, transport, and store energy in the material that contains the energy, we have a definite feeling for it. Its almost as though we should be able to pick up a handful of energy without picking up the material along with it. But, of course, we can't. We can do one more thing with it, though, we can "use" it. We can buy, sell, move, store, and "use" it. You need to be sure that you know what the expression "using energy" means.

## THE LAW OF CONSERVATION OF ENERGY

When we use a tank of gasoline, the gasoline is gone forever. Is the energy that the gasoline contained also gone forever? No, the energy was just transformed from chemical energy to other forms. Most of it was converted to heat. Some went out the exhaust. Some went with the air blowing through the radiator. Some was converted to heat as the automobile overcame road and air friction. Some was given off as sound. Some was converted to kinetic energy of the car, but, when the brakes were applied, even that was transformed to heat in the brake drums.

The energy in the gasoline was highly concentrated, but after it is used, it is distributed very widely in the atmosphere over a range of one or two hundred miles. Some of the energy may have been absorbed by the atmosphere to warm it ever so slightly. Some probably radiated to outer space. The energy in the tank has been used. It still exists but it is now in an unusable form. We cannot reuse it. It was not destroyed but we could never concentrate it as much as it was originally in the gasoline tank.

The energy was not destroyed; it cannot be destroyed. Energy cannot be created either. That is a law of nature: The law of conservation of energy.

> "Energy can be transformed from one form to another, but it cannot be created or destroyed."

Remember that energy is the ability to do work. How can work be done during the process when energy is being transformed from one form to another?

A few examples illustrate the answer. Chemical energy stored in gasoline is converted to heat during combustion. Gases expand when heated, perhaps in the cylinder of an engine, creating a force on the piston and making it move. The combination of force and movement indicates work being done. Dynamite moves rocks and trees in a similar way.

Gravitational potential energy of water behind a dam is converted to kinetic energy as it flows downhill. The gravitational force causes the water to move. Work is done on the water. Any moving object can do work. It can collide with other objects, exerting forces and causing motion. The moving water may be directed towards the blades of a turbine, exerting forces and causing rotary motion which can be used in many ways. Gravity also causes air to rise when it is heated. Moving air can cause rotary motion (windmills) the same way moving water does.

Kinetic energy of the rotating turbine is converted to electrical energy. Chemical energy in a battery or nuclear energy, can also be converted to electrical energy. Electrical energy may be the kinetic energy of electrons moving in a conductor, or in its pure form, may be stored in electric or magnetic fields. Whenever an electric current passes through a magnetic field, the wire conducting the current if forced to move. Thus, the magnetic fields cause rotary motion of the armature of a motor. Work is done by the magnetic field on the wires during the energy transformation.

Work is done by frictional forces when a car is stopped by pressing the brake. Kinetic energy is transformed to heat in the process.

## KINETIC ENERGY

Mechanical energy is kinetic, gravitation potential, and elastic energy. Changes in any of these involves a mechanical change in speed, position, or state of strain.

Kinetic energy is energy an object has when it is moving. The formula for kinetic energy is:

$$E_k = \frac{1}{2}mv^2$$

Where v is the object's velocity, and m is its mass.

Keep in mind that mass is weight divided by the acceleration of gravity ($m = w/g$) and must be calculated when using the British measuring system or substituted to get the formula:

$$E_k = \frac{wv^2}{2g}$$

Use the first equation with metric units and the second with British.

Example: How much kinetic energy does a 4000 lb automobile have when going 55 mi/h?

Given:

$w = 4000$ lb
$g = 32$ ft/s$^2$
$v = 55$ mi/h $= 80.67$ ft/s

$$E_k = \frac{wv^2}{2g} = \frac{4000 \text{ lb} \times (80.67 \text{ ft/s})^2}{2 \times 32 \text{ ft/s}^2}$$

$$E_k = 407\ 000 \text{ ft}\cdot\text{lb}$$

Notice that the units are the same as the units for work.

## GRAVITATIONAL ENERGY

Gravitational potential energy is energy an object has due to its position. It is given by the formula

$$E_G = mgh$$

where h is the vertical height from the zero reference level. The zero reference level may be chosen (by you) to be any horizontal plane near the object. For Brisish units use the formula:

$$E_G = wh$$

Example: A table, 1 m high, rests on the second floor 5 m above the ground. A 5 kg object is held 2 m above the table. Find its gravitational potential energy relative to the table top, floor, and ground level.

Given:

$h = 2$ m relative to the table top

$h = 3$ m relative to the floor

$h = 8$ m relative to the ground

$$m = 5\ \text{kg}$$

$$g = 9.8\ \text{m/s}^2$$

$$E_G = mgh = (5\ \text{kg})(9.8\ \text{m/s}^2)(2\ \text{m}) = 98\ \text{J (table)}$$

$$E_G = mgh = (5\ \text{kg})(9.8\ \text{m/s}^2(3\ \text{m}) = 147\ \text{J (floor)}$$

$$E_G = mgh = (5\ \text{kg})(9.8\ \text{m/s}^2(8\ \text{m}) = 392\ \text{J (ground)}$$

Again notice the units are the same as the units of work. An object positioned below the zero reference level is said to have negative gravitational energy. Work would have to be done on it to move it to the zero level, whereas an object with positive energy can do work when it arrives at the zero level, since it would now possess kinetic energy.

## ELASTIC ENERGY

When a spring is stretched the change in length is proportional to the stretching force, usually expressed as:

$$F = ky$$

Where k is called ths spring constant of the spring, and y is the increase in length due to the stretching force F. The spring constant tells you how much force is required to stretch a spring unit length. It normally has units of lb/ft, N/m, etc. It is a large number for stiff springs and a small number for weak springs.

Example: How far will a spring stretch if 5 lb is applied to it? 3 lb will stretch it 0.12 ft.

Given:

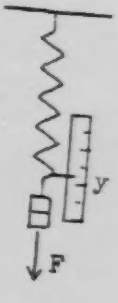
$$F = 5\ \text{lb}$$

$$F_1 = 3\ \text{lb}$$

$$y_1 = 0.12\ \text{ft}$$

$$k = F_1/y_1 = 3\ \text{lb}/0.12\ \text{ft} = 25\ \text{lb/ft}.$$

$$y = F/k = 5\ \text{lb}/(25\ \text{lb/ft}) = 0.2\ \text{ft}.$$



The energy (elastic) in a stretched spring is equal to the work done in stretching the spring. Since the amount of stretch is proportional to the stretching force, you must use the average force ($F_{av} = F/2$) in calculating the work done. The elastic energy stored in a spring is given by the formula:

$$Ee \tfrac{1}{2} ky^2$$

Example: Find the energy stored in the spring of the previous example when 5 lb is applied to it.

Given: $k = 25$ lb/ft

$y = 0.2$ ft

$$Ee = \tfrac{1}{2} ky^2 = \tfrac{1}{2} (25 \text{ lb/ft})(0.2 \text{ ft})^2$$

$$= 0.5 \text{ ft}\cdot\text{lb}$$

$$Wk = \tfrac{1}{2} Fs = \tfrac{1}{2} (5 \text{ lb})(0.2 \text{ ft}) = 0.5 \text{ ft}\cdot\text{lb}$$

## POWER

Power is the rate at which work is done or the rate at which energy is transformed.

$$P = Wk/t$$

Example: How much work can a 0.5 kW motor do in 1 h?

Given: $P = 500 \text{ W} = 500 \text{ kg m}^2/\text{s}^3$

$t = 3600$ s

$$Wk = Pt = (500 \text{ kg m}^2/\text{s}^3)(3600 \text{ s}) = 1\ 800\ 000 \text{ J}$$

Unit conversion factors between watts, kilowatts, horsepower, ft lb/s, and ft lb/min, can be found in your text.

When work is being done against a constant load so that motion remains constant, power is given by the formula:

$$P = Fv$$

An automobile going at constant speed on level ground would be an example of this.

Example: Find the horsepower developed by a truck to maintain 45 mi/h if the force of friction is 300 lb.

$v = 45$ mi/h $= 66$ ft/s

$F = 300$ lb

$$P = Fv = \frac{(300\ \text{lb})(66\ \text{ft/s})}{(550\ \text{hp/ft}\cdot\text{lb/s})} = 36\ \text{hp}$$

## EFFICIENCY

The efficiency of a machine or device that transfers or transforms energy, is the ratio of output work or power to the input work or power and is usually expressed as a percentage.

## THE WORK EQUATION

If energy is transformed so that forces are applied to an object, its velocity, position or state of strain will change. The original energy in any form is transformed to kinetic, gravitational potential, elastic, or some combination of these three. Usually elastic energy doesn't change unless stretching, bending, twisting, etc. take place as in a collision. In the following discussion, it is assumed that no springs, torsion bars, etc. are involved.

If there is a net change in the kinetic and gravitational potential energy that an object possesses, either the object gave up energy, or it absorbed energy from some other object. If an automobile's speed increases on a level road as an example, the increase in its kinetic energy must have come from the chemical energy in the gasoline. A force was applied to the automobile by the road and it acted through the distance covered while the accelerator pedal was down. The work done on the car is just equal to the change in kinetic energy:

$$\tfrac{1}{2}\,mv^2 - \tfrac{1}{2}\,mv_0{}^2 = Fs$$

Either side of the equation gives the amount of chemical energy used to accelerate the car and does not include the energy used to overcome friction and lost in the form of heat or sound.

Example: A car on the level road accelerates from 30 mi/h in distance of 300 ft. What is the average accelerating force on the car if its weight is 4000 lb?

Given:

$m = w/g = 4000\ \text{lb}/32\ \text{ft/s}^2 = 125\ \text{slug}$

$v = 45\ \text{mi/h} = 66\ \text{ft/s}$

$v_0 = 30\ \text{mi/h} = 44\ \text{ft/s}$

$s = 300\ \text{ft}$

$$\tfrac{1}{2}\,(125\text{ slug})(66\text{ ft/s})^2 - \tfrac{1}{2}\,(125\text{ slug})(44\text{ ft/s})^2 = F\cdot(300\text{ ft})$$

$$F = 504\text{ lb}$$

If the speed of the car had decreased from 45 mi/h to 30 mi/h in the same distance, the average braking force would have been 504 lb, also.

If motion up or down a hill is included, the work equation becomes:

$$\left(\tfrac{1}{2}\,mv^2 - \tfrac{1}{2}\,mv_0{}^2\right) + (mgh - mgh_0) = Fs$$

The first parenthesis contains the change in kinetic energy; the second contains the change in gravitational potential energy. If the zero reference level is chosen at the low point, then either h or $h_0$ equals zero, so the equation is simplified by one term.

In some situations where the external force is negligibly small, then the right side of the equation becomes zero. In that case, the change in kinetic energy equals the negative of the change in gravitational potential energy. An increase in one equals the decrease in the other.

Example: A pendulum swings out and upward a vertical distance of 4 cm. What is its speed as it passes through the low point of the swing?

Take the low point as the zero reference level,

Given:

$h = 0$

$h_0 = 4$ cm

$v_0 = 0$

$g = 980\text{ cm/s}^2$

Notice the mass is not given. However, since mass is in every term, it will drop out of the equation. The second and third term on the left and the term on the right drop out because they have a zero factor. So, the equation becomes:

$$\tfrac{1}{2}\,v^2 - gh = 0$$

$$\tfrac{1}{2}\,(v^2) - (980\text{ cm/s}^2)(4\text{ cm}) = 0$$

$$v = 88.5\text{ cm/s}$$

The force on the right side of the work equation is constant if the velocity doesn't change as when a car is on a hill with the engine or brakes maintaining a constant speed. Changes in speed mean changes in air resistance. If the change in air resistance is negligible, then Newton's second law of motion (module M 7) applies. Distance and time can then be calculated using kinematics (module M 5).

**Example:** A car coasts up a straight incline (I-80, Milford, west bound exit). It leaves the interstate (bottom of incline) at a speed of 45 mi/h. With the transmission in neutral, it coasts, reaching the top in 18.5 s, and still going 26 mi/h with space enough to stop at the stop sign. In order to measure the frictional force, the time for the car to coast through the same speed range on level ground was measured and found to be 29.5 s. Find the vertical height of the incline.

Given: $v_0 = 45$ mi/h $= 66$ ft/s

$v = 26$ mi/h $= 36.8$ ft/s

$t_x = 18.5$ s (on exit)

$t_\ell = 29.5$ s (on level)

$h_0 = 0$

Note: $F = ma = m\,\frac{(v - v_0)}{t_\ell}$ assuming force is nearly constant, and $s = \frac{(v - v_0)}{2}\,t_x$

so, the work equation becomes:

$$\left(\tfrac{1}{2}mv^2 - \tfrac{1}{2}mv_0^2\right) + (mgh - mgh_0) = m\,\frac{(v - v_0)}{t_\ell}\,\frac{(v + v_0)}{2}\,t_x$$

Note: m drops out and so does the term with $h_0$ so:

$$\tfrac{1}{2}(v^2 - v_0^2) + gh = \tfrac{1}{2}(v^2 - v_0^2)\,\frac{t_x}{t_\ell}$$

$$h = \frac{(v^2 - v_0^2)}{2g}\left(1 - \frac{t_x}{t_\ell}\right)$$

$$h = 16.9 \text{ ft}$$

This example was performed as an experiment at Milford and subsequent measurement of the vertical height with surveying equipment gave a value of 17.06 ft for comparison.

PROBLEMS

Module M 8 ENERGY & POWER

1. Does a man sitting still in a moving automobile possess kinetic energy? Explain.

2. A 5 kg mass is held 2 m above a 1 m table. One person says the mass has 98 J of gravitational potential energy and another says it has 147 J. Who is correct? Explain.

3. A bullet in a gun fires. The bullet, after traveling 100 yd, is imbedded in a sand bag. What was the original form of energy? What forms does it take while the bullet is moving? After being imbedded in the sand bag?

4. One car is at the top of a hill, the other only half way up. How does the gravitational energy relative to the bottom of the hill compare if they have the same weight? If one was moving at twice the speed as the other on level ground, how does their kinetic energies compare?

5. Are work, energy, and power vectors or scalar quantities?

6. Two springs have different spring constants. If they have equal lengths and are stretched by the same force, is more work done on the spring with the larger constant? Is more work done on the one with the larger constant if they are both stretched through the same distance?

7. What are the units of work, energy, and power in each of the cgs, MKS, and British measuring systems? Express each of these in fundamental units for each system.

8. How much work does a machinist do in lifting a 95 lb piece of metal onto a lathe bed 3.5 ft high?

9. A 1000 kg lathe is to be moved to a new location by pushing it on rollers. The distance to be moved is 50 m and the coefficient of friction is 0.12. How much work will be done?

10. An electric motor on a large drill press is rated at 2 hp. If the motor is 90% efficient, what is the electric input power in watts?

11. A gasoline engine has an efficiency of 25%. It is used to drive a generator for an electric welder. The generator is 65% efficient. If the output of the generator is 5.6 kW, what is the power delivered to the generator by the motor? What is the input power of the engine? If each gallon of gasoline contains 89 000 000 ft lb of energy, how long could the equipment be used if the tank holds 2.5 gal? (Assume continuous use, neglecting idle time)

12. A dowel pin is being driven into a die component. The hammer has a mass of 0.35 kg and is moving at a speed of 4.5 m/s just before contact with the pin. Find the average force on the pin if it is driven 1 cm by the blow.

13. A truck delivering oxygen tanks and other welding supplies has 500 lb of air resistance and road friction at 55 mi/h. How much power must the engine develop to maintain this speed?

14. A fork lift used in a manufacturing plant lifts a load of packaged castings, weighing 1150 lb including the weight of the pallet. If the load is lifted to a height of 4.5 ft, what is the increase in gravitational potential energy? How much power is required if the lifting is done in 8 s? If the hoist mechanism is 55% efficient, what power is delivered to the hoist by the engine?

15. A 400 lb ram on a shaper makes an 18 in stroke (forward and return). At its slowest speed, 10 cycles are completed each minute. Three-fifths of the time for one cycle is used on the forward stroke and two-fifths on the return. What is the average kinetic energy of the ram on the forward stroke? On the return stroke? At its fastest speed (129 cycles/min) find the average kinetic energy of the ram on each of the forward and return strokes.

16. A die used in an automatic punch press has a spring used for ejecting the finished product. If 22 lb of force will compress the spring 0.1 in, find the spring constant. How much energy is stored in the spring if it compresses 0.5 in when being used? How much energy is used in ejecting the pieces each minute if the press is operated at 120 strokes/min? What power in horsepower is required to operate the spring ejector?

17. A ventilator fan in a heat-treating room moves 120 $m^3$ of air per minute at a speed of 10 m/s. If each cubic meter of air has a mass of 1.293 kg, what is the kinetic energy of each cubic meter? What is the kinetic energy given to the air in 1 min? If the fan is 75% efficient, what power is put into the fan by the electric drive motor?

18. A hydraulic pressure of 1000 $lb/in^2$ applies a force of 4900 lb on a 2.5 in hydraulic cylinder. How much work does the piston in the cylinder do in moving the load 4 ft? If the motion requires 15 s, how much power is required?

ANSWER KEY (PROBLEMS)

Module M 8 ENERGY & POWER

1. Yes, relative to ground.

2. Both,98 J-zero reference is table, 147 J-zero reference is floor.

3. Chemical, kinetic, heat

4. 2:1, 4:1

5. Scalars

6. No (less), yes

7.

| | |
|---|---|
| erg, erg, erg/s | $g\ cm^2/s^2$, $g\ cm^2/s^3$ |
| J, J, W | $kg\ m^2/s^2$, $kg\ m^2/s^3$ |
| ft·lb, ft·lb, ft·lb/s | ft·lb, ft·lb/s |

8. 333 ft lb

9. 58 800 J

10. 1340 W

11. 8.62 kW, 34.5 kW, 2.43 h

12. 354 N

13. 73.3 hp

14. 5 175 ft·lb, 1.18 hp, .14 hp

15. 1.09 ft·lb, 7.17 ft·lb, 406 ft·lb

16. 2640 lb/ft, 2.29 ft lb, 275 ft·lb, 0.00833 hp

17. 259 J, 7760 J, 172 W

18. 19 600 ft·lb

EXPERIMENTS

Module M 8 ENERGY & POWER

**PURPOSE:** The purpose of this experiment is to study Hooke's law as it applies to springs and to study the work done on and the energy stored in a spring when it is stretched or compressed.

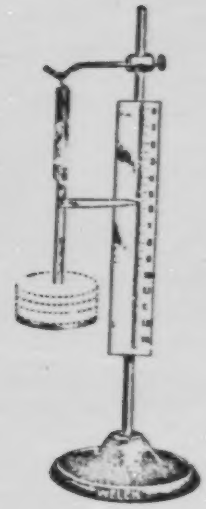
**CAUTIONS:**

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using.
3. Observe all cautions listed in the prodedure section of these instructions.

**EQUIPMENT:** Check to see if all the following equipment is available before you start.

1. Welch #569 Hooke's Law Apparatus
    - A. Stand with mirror scale
    - B. Weight hanger with pointer
2. Two spiral springs (one large, one small)
3. One set of slotted weights

**PROCEDURE:**



By permission: Sargent-Welsh Scientific Co., Instructions for Hooke's Law Apparatus

1. Set up the apparatus as shown in the diagram, supporting the large spiral spring vertically. The pointer should now be horizontal in front of the scale.

NOTE: The pointer is a part of the weight hanger. The scale has a mirror finish so you can eliminate parallax errors by reading the scale when the pointer is exactly in front of its image.

NOTE: To eliminate friction, add sufficient weights to the hanger so that the coils of the spring are slightly separated.

NOTE: Before starting your observations, be sure the pointer is near the top of the scale. Adjust by moving the spring hanger or the scale up or down on the stand. The pointer does not need to be set on zero.

2. Record the position of the pointer on the first line on the data sheet table. Read the position as accurately as you can.

3. Add a 50 g mass to the hanger and weight already in place. Read and record the new position.

4. Continue adding masses (50 g at a time) until a total of 250 g have been added. Read and record the position at each step.

5. Remove the masses in equal 50 g steps and record the position at each step.

   CAUTION: Do not add more than 350 grams to the spring. The spring will exceed the elastic limit of the metal and will not return to its original shape. The spring constant would be altered and the spring ruined.

6. Convert the masses to weight (stretching force) in dynes. Record in the table.

7. Plot a graph of the data (Force vs. displacement).

8. Does the result of the experiment thus far indicate that Hooke's law is correct? Answer this question on the data sheet.

9. Calculate the difference in successive readings of the position of the pointer. Record in the table. This gives the deflection of the spring for each 50 g step.

10. Calculate the average deflection of the spring.

11. Use the average deflection of the spring to calculate the spring constant in dynes/cm. See Information Sheets (green, pages) for discussion of springs.

12. Add 250 g to the hanger on the spring. (The deflection is already recorded in the data table.)

13. Calculate the energy stored in the spring.

14. What is the average force that stretched the spring in step 12? $(F_{av} = \frac{F + F_o}{2})$

15. Calculate the work done is stretching the spring in step 12. Use the average force (step 14) and the distance stretched (step 12).

16. Compare the results of steps 13 and 15.

17. Replace the large spring with the small one.

18. Record the position of the pointer.

19. Add masses in 10 g steps until you have added a total of 30 g to the hanger. Record the position of the pointer at each step.

20. Plot the data on the same graph as before.

21. Calculate the spring constant for this spring.

22. Is the slope of the graph greater or smaller than with the stiffer spring?

23. Is the spring constant larger or smaller than that for a stiffer spring?

24. Energy is stored in a stretched spring. What happens to this energy when the spring is released?

25. Replace the small spring with the large one.

26. Record the position of the pointer. (1st position)

27. Place 200 g on the hanger and record its position (2nd position).

NOTE: If you gently lower the hanger to the 2nd position, the spring will not oscillate. However, if the hanger is held in the 1st position and suddenly released, it will fall to a 3rd position well below the 2nd and then oscillate for a long time.

28. Determine the 3rd position, approximately, after two or three trials.

29. Calculate the gravitational potential energy of the 200 g mass in the 1st position relative to the 2nd.

30. Calculate the amount of stretch the spring would have if all the gravitational potential energy were transformed to elastic potential energy.

31. Compare the results of step 28 and step 30.

NOTE: In the 2nd position, 50% of the original gravitational energy is stored as elastic energy (see steps 15 and 16). If the 200 g mass is lowered gently, the other 50% is lost. If it is released suddenly, the other 50% becomes kinetic energy at the 2nd position.

26. Replace the large spring with the small one.

27. Record the position of the pointer.

28. Add masses in 5 g steps until you have added a total of 20 g to the hanger. Record the position of the pointer at each step. Calculate the differences in successive readings and average.

29. Plot the data on the same graph as before.

30. Calculate the spring constant for this spring.

31. Is the slope of the graph greater or smaller than with the stiffer spring?

32. Is the spring constant larger or smaller than that for a stiffer spring?

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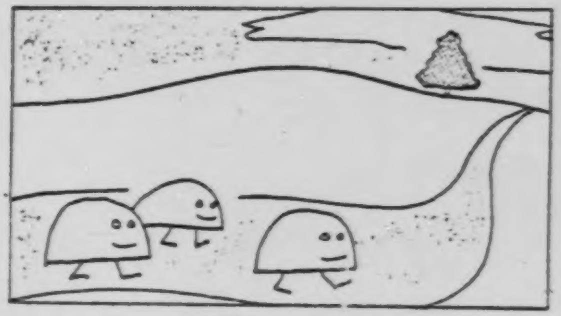
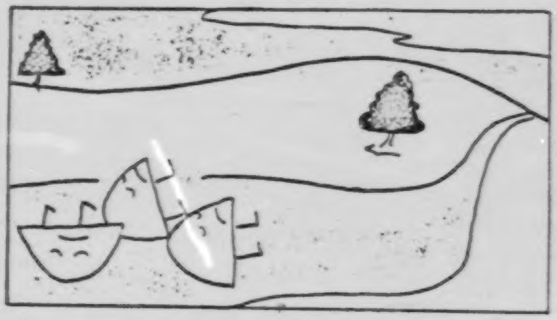
## THE DYNESAURS



*Question:*
If the "things" at right are centimeters, what are those below?



*Answer:*
They are ergs, of course, because ergs are dyne-centimeters.

Gene Waring

*Reprinted from* THE PHYSICS TEACHER

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 9

Title: SIMPLE MACHINES

Module Contents:
1. Mechanical advantage
2. Efficiency
3. Lever, inclined plane, and hydraulic jack
4. Modifications of basic machines
5. Compound machines

Program: This module has been prepared especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to introduce words, terms, and concepts associated with simple machines. You, as a manufacturing technician, will spend much of your time repairing, adjusting, or operating the many mechanical, electrical, or hydraulic machines of industry, or their controls. It is also necessary that you learn to speak the language associated with machines.

Producer: Gene Waring

Date Produced: October, 1976

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STUDENT INSTRUCTIONS

Module M 9 SIMPLE MACHINES

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define the following words and terms: machine, actual mechanical advantage, theoretical mechanical advantage, and efficiency.

2. Describe the lever by constructing simple diagrams of each of its three classes, showing input and output forces and lever arms.

3. List several examples of uses for each of the three classes of levers.

4. Describe the following modifications of the lever: wheel and axle, pulleys, block and tackle, and differential pulley by constructing diagrams of each showing input and output forces and movements.

5. Describe the inclined plane and the following modifications of it: wedge, cam, screw, and screw jack by constructing diagrams of each showing input and output forces and movements.

6. Describe the hydraulic jack by constructing diagrams showing input and output quantities.

7. Calculate the TMA, AMA, and efficiency for each of the basic machines and their modifications listed in objectives 4, 5, and 6; given the quantities required for the calculation.

8. From a list of input and output forces and movements, AMA, TMA and efficiency that describes a given machine, calculate those that are unknown and the work input and output.

9. Calculate the overall mechanical advantage of two or more machines set up in a "train" arrangement where one machine drives another.

10. State the principle of work (law of conservation of energy) as it applies to machines.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of simple machines. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 7) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 5).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook, plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 7). The information sheets cover subject matter that is presented briefly or not at all in some of the textbooks.

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B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read Chapter 6, sections 6.1-6.8 and sections 6.17-6.31, pages 137-144 and 151-169. Also read Chapter 11, sections 11.7-11.8, pages 273-277. (Note: Read either A or B, but not both)

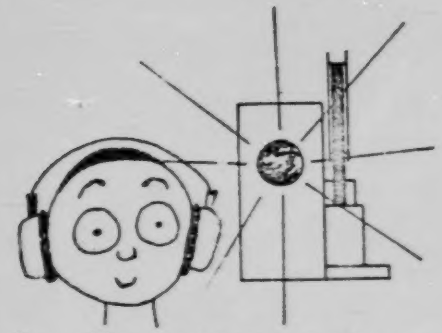
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read Chapter 7, sections 7.8-7.9, pages 85-87 and Chapter 12, section 12.5, pages 154-155.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read Chapter 10, sections 10.1-10.12, pages 118-141 and Chapter 15, section 15.4, pages 201-203.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read Chapter 12, sections 12.1-12.5, pages 168-183 and Chapter 13, section 13.4, pages 190-192.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read Chapter 12, sections 12.1-12.5 and 12.8-12.10, pages 175-183 and 188-193; and Chapter 14, section 14.2, pages 215-217.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. The Action of the Lever I, (EBE S-80824)
B. The Action of the Lever II, (EBE S-80825)
C. The Action of the Lever III, (EBE S-80826)
D. The Inclined Plane, (EBE S-80827)
E. The Pulley I, (EBE S-80828)
F. The Pulley II, (EBE S-80829)
G. The Screw, (EBE S-80830)
H. The Wedge, (EBE S-80831)
I. The Wheel and Axle, (EBE S-80832)

A 16 mm movie is available in the LRC. Its title is: From Muscle to Machine, (Educational film series) and is an excellent film supplement for this module. Try to arrange a viewing time when several of your classmates can join you. The LRC staff will show you how to operate the movie projector.

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving simple machine problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional proctice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are three experiments for most students in this module. They will give you practice in learning about mechanical advantage and efficiency, as well as, general problems associated with simple machines.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

Electronics students should perform two of the first three experiments and experiment 4.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for staisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module M 9 SIMPLE MACHINES

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The theoretical mechanical advantage of simple machines cannot be less than one.

T - F 2. The AMA of a machine is always less than the TMA.

T - F 3. A machine can be made to increase force and decrease speed at the same time.

T - F 4. A screw-jack is a modification of the inclined plane.

T - F 5. The work output of a machine is the work input plus the work done against friction.

6. On a block and tackle, an input force of 500 N, pulled through 18 m, raises a load of 4000 N while lifting it 1.8 m in 18 s. The TMA is:

a) 8
b) 10
c) 0.125
d) 0.1

7. What is the TMA of a differential pulley if the "wheel" radius is 8 in and the "axle" radius is 7.25 in?

a) 21.3
b) 7.63
c) 19.3
d) 1.1

8. The TMA of an inclined plane is 4 and its efficiency is 60%. What is the AMA?

a) 6.7
b) 24
c) 2.4
d) cannot be calculated

9. A differential pulley hoist is used to lift a 295 N engine, 2.5 m. If the efficiency is 75%, how much work is done to overcome the internal friction of the hoist?

10. The TMA of a handle on a hydraulic jack is 9. If the overall TMA of the lever-jack combination is 150, what is the TMA of the hydraulic mechanism?

## ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 9 SIMPLE MACHINES

| Question-Answer | | If you missed this question, you are directed to these learning activities |
|---|---|---|
| 1. | F | I. Reading |
| 2. | T | I. Reading or II. Listening/Viewing |
| 3. | T | I. Reading or II. Listening/Viewing |
| 4. | T | I. Reading |
| 5. | F | I. Reading or V. Experiments |
| 6. | b | III. Solving Problems |
| 7. | a | III. Solving Problems |
| 8. | c | III. Solving Problems or V. Experiments |
| 9. | 246 J | III. Solving Problems or V. Experiments |
| 10. | 16.7 | III. Solving Problems or V. Experiments |

INFORMATION SHEET

Module M 9

## SIMPLE MACHINES

Any mechanical device that aids man in doing work can be called a machine. There are two basic types: those that transform energy from one form to another, and those that transmit energy from one place to another. Six categories or classes of the two basic types are:

1. Devices in which the driving force is increased but the speed of the movement is decreased. Block and tackles, screws, incline planes, and some levers, gears and pulleys are examples of this class. This class of machine makes it possible to lift very heavy loads by applying relatively small forces.

2. Devices in which the driving force is decreased but the speed of the motion is increased. In situations where the driving force is applied to the short end of a lever or to the largest of two gears or pulleys the device becomes one of this type. This class of machine makes it possible to move objects very rapidly.

3. Devices that transmit mechanical energy or work without increases or decreases in the forces or speed of the movement. These devices merely provide a person with a more convenient way of doing work by pulling or pushing in a different direction or a more convenient place to apply the driving force. Examples are: using a single pulley to pull downward to lift a load; using a wire chain or load to apply a push or pull to another device some distance away (such as a hand choke on a car or a chain pull on a light switch); and using a drive shaft or cable to transmit rotary motion (such as a speedometer cable or drive shaft on a car). Idler gears, certain pulleys and hydraulic hoses are other examples.

4. Devices that transmit energy or material without doing work against external forces. These are normally called conduits. Examples are: water, oil, and gas pipelines; electric transmission lines; and heat ducts. Note that the incline plane is more than a conduit since work is done against the external force of gravity. Automobiles, trucks, trains, airplanes, and ships used in conjunction with roads, rails, airways, and waterways are conduits of energy and materials also. Compare the efficiency of moving materials through modern conduits to the methods used in ancient Egypt while building the pyramids.

5. Devices that convert energy from one form to another in which the final form is not mechanical energy (kinetic, gravitational, or elastic). Furnaces, boilers, solar collectors, refrigerators, electric generators, electric transformers, etc., are examples of this type.

6. Devices that convert energy from one form to another in which the final form is mechanical energy. Examples are: steam, gasoline, and diesel engines; steam, water, or gas turbines; rockets; guns and cannons; electric motors and solenoids; etc.

There are mechanical devices that do not·transmit or transform energy and therefore are not classified as machines. Devices such as bolts, nails, rivets, staples, etc., are used to hold other objects together and are classified as fasteners. Devices such as cantilever beams, trusses, footings, etc., are used to carry the weight of other objects and may be classified as supports. Even though these devices exert forces or torques, once in place, there is no movement so they do not aid man in doing work.

The first three categories of machines are those that transmit energy and do work against external forces. These three catagories are classified as simple machines, the subject of this module. The other catagories are discussed in modules on fluid flow, electricity, and heat.

## THE BLACK-BOX SIMPLE MACHINE

Simple machines have enough common aspects that a general description can be given without discussing specific distracting mechanisms. All simple machines have an input side and an output side. Suppose a certain mechanism is hidden in a black box as shown in figure 1. Two ropes hang from the box, one carrying a load to be lifted. The other rope is the input rope and is pulled downward to lift the load. The input force ($F_i$) is applied to the input rope and pulled downward through an input distance ($s_i$). The work input is $Wk_i = F_i \cdot s_i$ and the power input is the work input divided by the time required for the movement to take place ($P_i = Wk_i/t$).

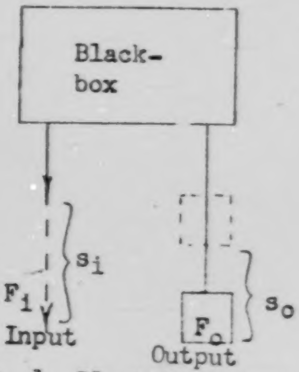


Fig 1. Black-box simple machine.

Similarily, the output force ($F_o$) resists the movement of the output rope. In this case, it is the weight being lifted. In other situations, it might be the resistance offered by a nail being pulled or the squeeze on the brake linings when brakes are applied. The output distance ($s_o$) is the distance that the object being lifted (or offering resistance) moves during the time the input force moves through the input distance. Work output is $Wk_o = F_o\ s_o$, and power output is $P_o = Wk_o/t$. The time for both input and output power calculations is the same.

The mechanical advantage of the machine is given by the ratio of output force to input force. This ratio is called the actual mechanical advantage (AMA). Since the input force must overcome the friction within the machine as well as lift the load, the force ratio is a measure of the actual performance of the machine.

$$AMA = \frac{F_0}{Fi} \qquad 1.$$

The theoretical mechanical advantage (TMA) is what the ratio would be if the machine had no internal friction and is generally based on the geometry of the machine. (Some texts use the term ideal instead of theoretical so, IMA and TMA mean the same thing.) If there were no internal friction, the output work would equal the input work. The TMA then, is the ratio of input distance to output distance:

$$TMA = \frac{si}{s_0} \qquad 2.$$

The AMA can usually be increased by oiling the machine to reduce friction. As friction is reduced, the AMA increases to a value that approaches the theoretical value. Friction cannot be eliminated completely, so the AMA will always be slightly less than the TMA. Note: The TMA doesn't change since it is based on the internal dimensions of the machine.

A slightly different approach to the subject involves the law of conservation of energy or the principle of work. The work input is used, not only to lift the load, but part of it must do work to overcome friction:

$$Wki = Wkf + Wk_0 \qquad 3.$$

Where Wkf is the work done against friction and is lost in the form of heat or sound. Since Wkf is never zero the ratio of $Wk_0$ to Wki is always less than 100%. This ratio is called efficiency:

$$Eff = \frac{Wk_0}{Wki} \times 100 \qquad 4.$$

Another formula for efficiency is the ratio of power output to power input since time for the work to be done is the same on the output side of the machine as on the input side.

$$Eff = \frac{P_0}{Pi} \times 100 \qquad 5.$$

Equation 4 is the definition of efficiency. The formulas for work were given previously, so:

$$\text{Eff} = \frac{\text{Wk}_o}{\text{Wki}} = \frac{F_o\,s_o}{\text{Fi}\,\text{si}} = \frac{F_0/\text{Fi}}{\text{si}/s_0}$$

Hence: $$\text{Eff} = \frac{\text{AMA}}{\text{TMA}} \times 100 \qquad 6.$$

Equation 6 gives another formula for efficiency. The following example illustrates the use of the first six equations.

Example: A certain machine has an efficiency of 80%. A 1000 N load is lifted 3 m by an input force of 250 N. Find the: AMA, TMA, input distance, work input, work output, and work done against friction. Check the efficiency with equation 4.

Given: $F_o = 1000$ N $\quad s_o = 3$ m

$\text{Fi} = 250$ N $\quad \text{Eff} = 80\%$

$\text{AMA} = \frac{1000\text{ N}}{250\text{ N}} = 4$ Equation 1

$\text{TMA} = \frac{4}{.8} = 5$ Equation 6

$\text{Si} = (3\text{ m})(5) = 15\text{ m}$ Equation 2

$\text{Wki} = (250\text{ N})(15\text{ m}) = 3750\text{ J}$ Definition of work

$\text{Wk}_o = (1000\text{ N})\ (3\text{ m}) = 3000\text{ J}$ Definition of work

$\text{Wkf} = 3750\text{ J} - 3000\text{ J} = 750\text{ J}$ Equation 3

$\text{Eff} = \frac{3000\text{ J}}{3750\text{ J}} \times 100 = 80\%$ Check

If the time for the work to be done was known, the power input and power output could also be calculated.

The basic qualities of simple machines are presented as definitions or formulas in the first six equations. These equations apply to all simple machines. Equation 3 defines the TMA. Sometimes though it is difficult to measure the input and output distance. Since the TMA is based on the geometry of the machine, it can usually be expressed in simpler and more easily measured quantities. The specific formulas depend on the specific type of simple machine.

LEVERS

A quick stroll around a machine shop or an automotive repair shop would show many uses of the lever. It is, perhaps, the simplest and most widely applied mechanical device in industry. Levers fit all three of the categories of machines classified as simple machines. Usually, however, levers are divided into three classes in a different way.

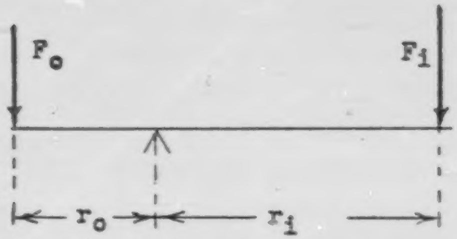


Fig 2. First class lever

The first class lever (figure 2) has the input force applied at one end of the lever, and the output force at the other. The fulcrum or pivot point is in between. Pry-bars are usually used this way. Equation 1 defines the AMA.

The input and output movements are along an arc and are difficult to measure. The same ratio is given by the ratio of lever arms, however:

$$\text{TMA} = \frac{r_i}{r_0} \qquad 7.$$

Notice that the fulcrum may be located at any point between the ends. The TMA will be very small (near zero) when the fulcrum is near the right end and very large near the left. Thus, we can say that:

$$0 < \text{TMA} < \infty$$

The symbol (<) means "less than: and (>) means "greater than." The symbol (∞) means infinity. A first class lever can have a TMA of any number between zero and infinity. A practical machine, however, cannot have a mechanical advantage of zero or infinity. What would this mean? An infinite MA means infinite movement on the input side with just slight movement on the output side. For practical purposes, the use of the word "infinity" to indicate the mechanical advantage ratio, will mean a large number perhaps 100 or 200.

Consider a TMA equal to one. Input and output movement must be equal. Lever arms must be equal. A TMA equal to more than one means greater input movement than output (greater input lever arm) but an input force less than the output force. A TMA less than one means less movement but greater force requirement on the input side.

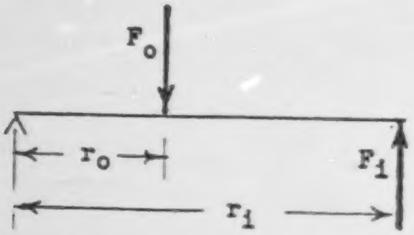


Fig 3. Second class lever

The second class lever is described in figure 3. The output force (load) being located between the fulcrum and the input force. Note that $r_i$ is always greater than $r_o$, so the TMA is always greater than 1:

$$1 < \text{TMA} < \infty$$

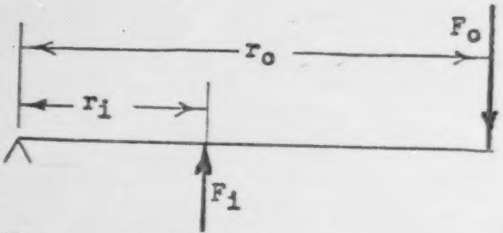


Fig 4. Third class lever

The third class lever is shown in figure 4. The input force is between the fulcrum and the load. Note that $r_o$ is always greater than $r_i$ in this one, just opposite to the second class lever. The TMA must be less than 1:

$$0 < \text{TMA} < 1$$

Most textbooks give several examples of each class.

WHEEL AND AXLE

Any wheel, crank handle, gear or pulley that is rigidly attached to an axle is called a wheel and axle. Figure 5 illustrates the machine, showing the input and output forces applied to ropes. The forces could be applied to gears or pulleys by other gears or V-belts instead. Figure 6 shows an end view of the wheel and axle. If all dashed lines are erased, you can readily see that the wheel and axle is really just a first class lever. It allows continuous movement in contrast to a regular lever used as a pry. Notice that the lever arms ($r_o$ and $r_i$) are measured from the fulcrum (the axis of rotation). The TMA has the same formula as the lever (equation 7).

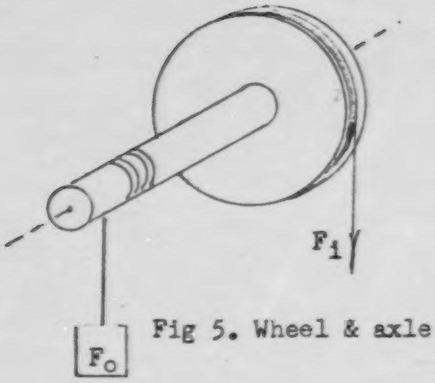


Fig 5. Wheel & axle

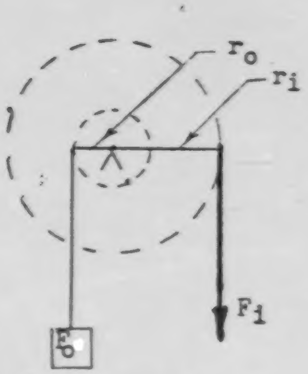
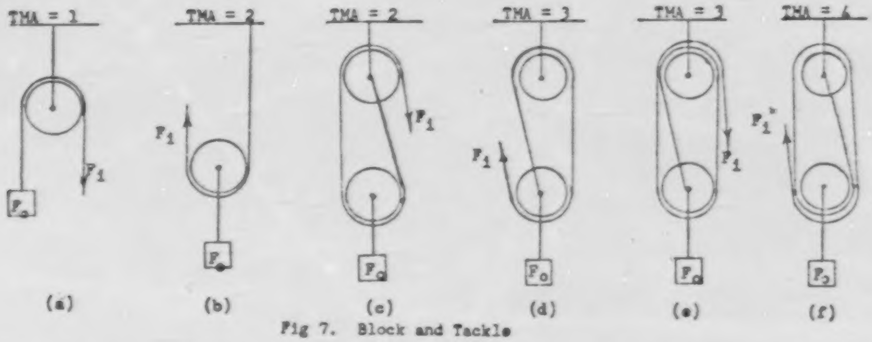


Fig 6. End view.

BLOCK AND TACKLE

Pulleys (sheaves) are sometimes arranged in blocks. Ropes or cables connect the pulleys to form a simple machine called a block and tackle. See figure 7.



(a) (b) (c) (d) (e) (f)

Fig 7. Block and Tackle

Arrangement (a) is a single pulley and allows a downward pull to lift the load (TMA = 1). Arrangement (b) is also a single pulley but an upward pull is applied. If the end of the rope moves upward 2 ft, one foot comes from the rope on each side of the pulley so the load is lifted 1 ft (TMA = 2). Arrangement (c) adds a pulley to allow a downward pull but is otherwise identical to (b). Turning (c) upside down gives arrangement (d). The load will lift 1 ft when the end of the rope is raised 3 ft (TMA = 3).

Arrangement (e) is the same as (d) except a second independent sheave has been added to the upper block to allow a downward pull. (Two ropes going over the upper block indicates two independent sheaves.) Arrangement (f) is the same as (e) except turned upside down. The TMA is increased to 4.

The TMA for block and tackles can easily be found by counting the ropes that directly support the load. You can draw the diagrams for block and tackles with more and more sheaves in both blocks, giving higher and higher mechanical advantage.

$$\text{TMA} = \text{number of ropes directly supporting load} \qquad 8.$$

DIFFERENTIAL PULLEY

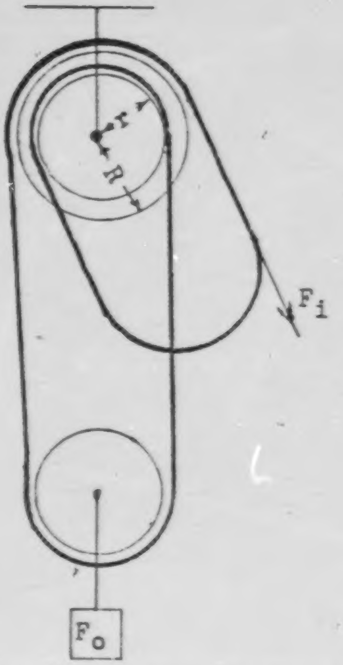


Fig 8. Differential pulley

A wheel and axle and a single pulley are used to form the differential pulley. They are connected by a single continuous chain as shown in figure 8. The chain rides in grooves so no slippage occurs.

If the input force pulls the chain through one circumference of the wheel and axle (a distance of $2\pi R$ , a length of chain $2\pi r$ will unwind off the axle. At the same time, the chain on the left side of the single pulley will raise a distance $2\pi R$ pulled from above. So, the load will lift a distance of $\frac{1}{2}$ ($2\pi R - 2\pi r = \pi(R-r)$. The TMA is therefore, the ratio of $2\pi R$ to $\pi(R-r)$ or, simplified is:

$$\text{TMA} = \frac{2\ R}{(R-r)} \qquad 9.$$

Notice that the smaller the difference in the size of the wheel and axle the greater the TMA.

INCLINE PLANE

Up to this point, the only simple machines that have been discussed have been modifications and variations of the lever. A second basic machine which has several variations is the inclined plane.

Less force is required to push a load up an incline against friction and a portion of gravity than it takes to lift it directly.

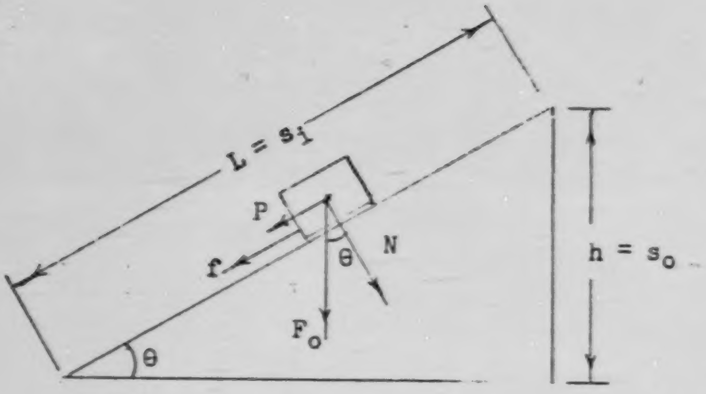


Fig 9. The inclined plane.

The output force is the load being raised and the output distance is the vertical rise (see figure 9). The input distance is the length of the incline. The input force is the force required to push the object up the incline. The TMA is given by equation 2, or:

$$\text{TMA} = \frac{L}{h} \qquad 10.$$

Note that this is the reciprocal of the sine of the angle of incline:

$$\text{TMA} = \frac{1}{\sin \theta} \qquad 10\text{ a.}$$

The force (input) required to push the object up the incline is the sum of the frictional force ($f = \mu W \cos \theta$) and the component down the incline ($P = W \sin \theta$). So, the AMA, after substituting in equation 1 and simplifying, becomes:

$$\text{AMA} = \frac{1}{\mu \cos \theta + \sin \theta} \qquad 11.$$

so, the AMA depends only on the coefficient of friction ($\mu$), and the angle of the incline ($\theta$). Similarily, equation 6 for efficiency becomes:

$$\text{Eff} = \frac{1}{(\mu/\tan \theta) + 1} \times 100 \qquad 12.$$

WEDGES AND CAMS

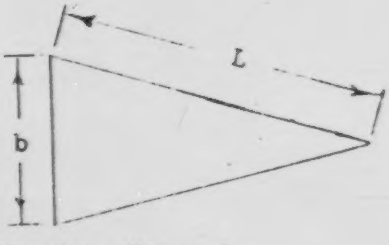


Fig 10. The wedge

The wedge is a double inclined plane. Its TMA is given by the formula:

$$\text{TMA} = \frac{L}{b} \qquad 13.$$

where b is the thickness at the butt or base end. The wedge is used for applying a force perpendicular to the direction it is being driven, such as splitting logs. Note that the sharper the wedge, the greater the mechanical advantage.

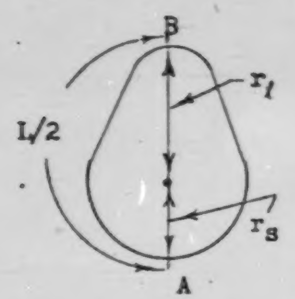


Fig 11. The cam

The cam is another variation of the incline plane. Cams are used to open and close valves and switches. The lift provided by the cam may not be proportional to the angle of rotation, so the mechanical advantage on some cams is variable. The lifting takes place as the cam slides against the push rod (for example) as it travels half the distance around the cam. The input movement is half the distance around the cam (L/2) and the output is the push rod movement (largest radius minus the smallest radius). The average TMA is:

$$\text{TMA} = \frac{L}{2(r\ell - rs)} \qquad 14.$$

SCREWS

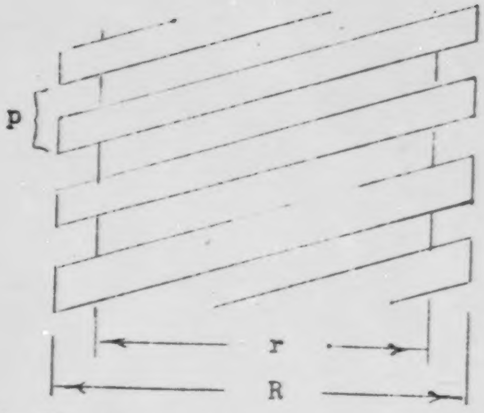


Fig 12. The screw

A screw is a modification of the inclined plane. The inclined plane is wrapped around a cylinder. A screw jack, for example, is used to lift various loads. The distance between threads is called the pitch (p). It is the distance the load is lifted or advanced in one complete turn of the handle. ($s_0$ = p)

The load effectively rides up the incline as the handle is turned. The input distance in one revolution is approximately the average circumference of the threads. The average radius (r) is halfway between the crest (outside) radius (R) and the root (inside) radius. The average circumference (input distance) is $\pi(R + r)$. The input distance in one revolution is actually the distance around, but spiraled upward one thread.

In one automobile bumper jack, the actual input distance was 45.2 mm, where the average circumference was 44.2 mm, an error of 2.2%. The error will generally be less since this jack had a high pitch to circumference ratio. For all practical purposes, the TMA then is:

$$TMA = \frac{\pi(R + r)}{p} \qquad 15.$$

Note that this is the TMA for the screw only and does not include the mechanical advantage provided by the handle (lever). (The input lever arm is the handle length, the output is the average radius of the screw.) Equations 11 and 12 can be modified to fit the screw also, for example, the efficiency formula is approximately:

$$Eff = \frac{1}{[\mu p/\pi(R+r)] + 1}$$

Since the coefficient of friction is difficult to measure, this formula is not very useful. It is interesting, however, to note that the efficiency doesn't depend on the object being lifted. It depends only on the internal friction and the dimensions of the screw itself. The coefficient of friction must be large enough to prevent the weight from spiraling back down the screw when the handle is released. The "angle" must be less than the angle of repose. Most texts state that this means the efficiency must be less than 50%. Screws are not very efficient machines.

WORM GEAR

A worm gear is a screw device that applies a force on the teeth of a large gear. It transfers rotation around one axis to slower rotation around an axis at right angles to the first (see figure 13). The screw must make one complete revolution to make the gear advance one tooth. The screw must turn as many revolutions as there are teeth on the gear to make the gear rotate one time. The TMA equals the number of teeth on the gear.

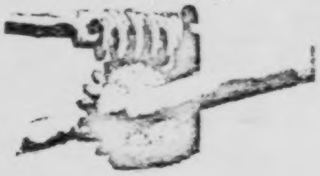


Fig 13. Worm gear.

HYDRAULIC AND PNEUMATIC MACHINES

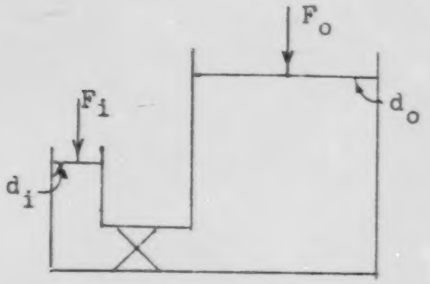


Fig 14. Hydraulic jack.

Hydraulic cylinders transfer forces and motion efficiently, smoothly, and (in the case of car brakes) evenly. Pascal's principle (see module P-4) states that "changes in pressure within an enclosed fluid is transmitted to every point within the fluid." Generally, this means that the pressure is the same on both input and output pistons (see figure 14). The larger piston will exert a larger force than a small one because of its larger area. (Pressure equals force divided by area.)

$$\frac{F_i}{A_i} = \frac{F_0}{A_0}$$

Where A is the area of the pistons. Since area is proportional to the square of the diameter, the theoretical mechanical advantage is given by the ratio of the square of the diameter:

$$TMA = \left(\frac{d_0}{d_i}\right)^2 \qquad 16.$$

The AMA and efficiency are given by formulas 1 and 6, respectively.

In the use of the hydraulic or pneumatic cylinders (see figure 14), there is usually no input piston as there is in the hydraulic jack. On the input side, pressure is applied by a hydraulic pump or by compressed air. The load the cylinder can lift is given by the pressure formula:

$$F_0 = PA_0$$

where P is the pressure applied.

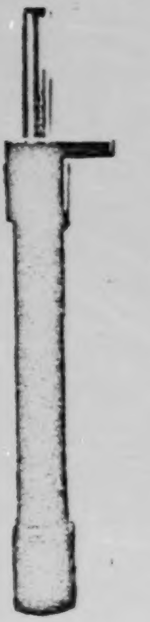


Fig 15. Hydraulic cylinder

COMPOUND MACHINES

In many applications of machines, two or more simple machines are used to form a compound machine. A screw mechanism is driven by a handle (lever) or by a gear. A hydraulic jack has a handle. Gears drive a cam shaft. There are many, many examples.

In each case, the output of one simple machine is the input of the second, the output of the second provided the input to the third, etc. It is easy to find the overall mechanical advantage or efficiency of such "train" arrangements of simple machines. Just multiply the quantity for the individual components. The overall TMA is:

$$(TMA_0) = (TMA_1)(TMA_2)(TMA_3)\ldots. \qquad 17\ a.$$

Similarily:

$$(AMA_0) = (AMA_1)(AMA_2)(AMA_3)\ldots. \qquad 17\ b.$$

and . . .

$$(Eff_0) = (Eff_1)(Eff_2)(Eff_3) \ldots. \qquad 17\ c.$$

Example: The AMA of the hydraulic mechanism of a jack is 6 and of the lever is 11. What is the overall AMA?

$AMA_0 = (6)(11) = 66$

Example: If the TMA of the jack of the parts in the previous example is 7 and 12 respectively, find the overall TMA and efficiency.

$TMA_0 = (7)(12) = 84$

$Eff = 6/7 = 85.7\%$ Hydraulic mechanism

$Eff = 11/12 = 91.7\%$ handle

$Eff_0 = (86\%)(92\%) = 78.6\%$

$Eff_0 = 66/84 = 78.6\%$ Check

## GEARS AND PULLEYS (TORQUE TRANSMISSION)

The simple machines discussed previously all transmit amplified or reduced forces with corresponding inverse changes in linear motion. Gears and pulleys do not do this. When two gears are in mesh, one tooth exerts a force on another. These are action-reaction forces and are, therefore, equal. Also, since the movement of one tooth on one gear causes the same amount of movement of the other gear, the surface speeds of the gears are equal. The same is true of pulleys driven by flat or "V" type belts.

However, even though the forces are equal, they are not applied at the same distance from the axis of rotation. Torques are increased or reduced. Likewise, the rotational speeds are increased or decreased. Torque ratios and speed (rotational) ratios describe the transmission of power by gear or pulley trains.

A complete discussion of gears and pulleys, as well as, power transmission is included in module M-11, after the study of circular motion (module M-10).

PROBLEMS

Module M 9 SIMPLE MACHINES

1. The lever, inclined plane, and the hydraulic jack are the three basic simple machines. List several modifications or variations of each.

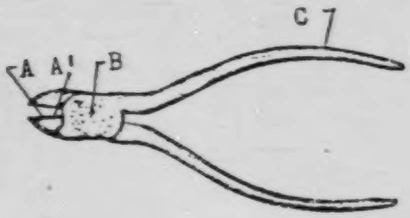
2. Make a list of several examples of each of the three classes of levers.

3. What is a force advantage? How is a speed advantage different? What is the mechanical advantage in each case?

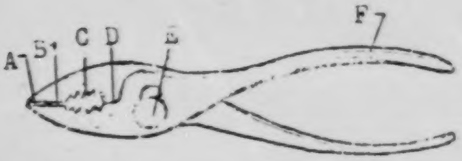
4. How does lubrication affect the TMA, AMA, and efficiency?

5. How does the amount of work done internally against friction affect the efficiency of a machine?

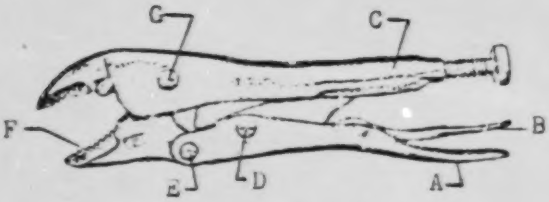
6. Discuss the following quantities and how they are related: work input, work output, work done against friction and efficiency.

7. 

Pliers, diagonal (dikes) wire cutters, and other similar clamping or cutting tools are two levers acting together. The fulcrum is at point B (see diagram). If the force is applied at point C, 10 cm from the fulcrum and a wire is cut at point A (near the center of the cutting edge) 1.7 cm from B, what is the TMA? What is the TMA if the wire is cut at A', 1.3 cm from B. What class lever is this?

8. 

The pliers shown may be used to grip objects at points A, B, or C and to cut wire at point D. The distances to the fulcrum E are: 4.5, 4, 2.5, and 1.5 cm, respectively. Find the TMA in each case if the force is applied at point F, 9 cm from the fulcrum.

9. 

The lower part (EDA) of the handle of a vise-grip pliers is a lever. It pivots at point E, applies a force on the toggle joint at point D by the action of a gripping force applied at point A. A snug grip on the object being clamped can be accomplished by a 7 lb force at point A. If the distance EA is 5 in, and the distance ED is 1.25 in, what is the TMA of the handle? What class lever is it? What force will be applied to the toggle joint by a 7 lb input force if the lever is 95% efficient?

10. The toggle joint of the vise-grip pliers of problem 9 is a machine based on the lever. (See problems 13 and 15 of module M 3). Section ED of the handle serves a double purpose since it is one section of the toggle joint, also. The other section is DC. The force applied by the handle at point D is 26.6 lb. This exerts a force of 1270 lb on point E of the lower jaw along a line DE. What is the AMA of the toggle joint? If the efficiency is 90%, what is the TMA?

11. The lower jaw of the vise-grip in problem 9 is also a lever pivoting at point G. If a force of 1270 lb is applied at E, perpendicular to line GE, what force is applied to the object being clamped at point F? The distance GE is 1.5 in and GF is 1.88 in and the lever is 90% efficient. What is the TMA and the AMA?

12. A 7 lb force is applied to the handle of the vise-grip in problem 9. The output force is 911 lb. What is the overall AMA, TMA, and efficiency? Refer to problems 9, 10, and 11 and treat the vise-grip as a compound machine. Note: A larger input force will result in a greater output force but mechanical advantage and efficiency will remain unchanged. Adjustments of the screw at point C would change them slightly.

13. A shop vise has a screw of 6.25 mm pitch. The outside thread diameter is 2.12 cm and the root diameter is 1.60 cm. The length of the handle is 23 cm. Find the TMA of the handle and of the screw. What is the TMA for the compound machine? If the overall efficiency is 35%, how much clamping force is developed at the jaws if 150 N is applied on the handle?

14. A crank that moves the carriage on a precision lathe has a radius (crank arm) of 5 cm. Rotation of the crank causes the carriage to move straight back and forth along the lathe bed by means of a series of gears. If the carriage moves 12.85 cm in five revolutions of the crank, what is the compound TMA?

15. The feed screw on a lathe has a pitch of 3.18 mm. How many revolutions does the spindle make for one revolution of the feed screw if the feed is set at 0.0381 mm per revolution of the spindle? What is the TMA of the compound machine that transmits motion between the spindle and feed screw?

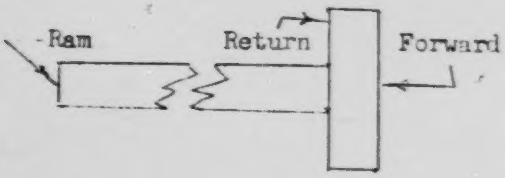
16. A 100 ton roll-bed hydraulic press used in a machine shop, has a ram (output) that is double-acting to provide either push or pull. The hand-operated pump has a handle 22.5 in long and an output lever arm 1.25 in long. What is the TMA of the handle? If the handle is 90% efficient, what is the AMA? A force of 40 lb on the handle will exert what force on the input piston?

17. The shop press in problem 16 has a ram (output) piston diameter of 5.05 in. The two-speed pump (input) has a piston of 2.66 in diameter for fast travel and of 0.54 in to exert large forces. The switchover from one input piston to the other is accomplished by hydraulic pressure. Find the TMA of the hydraulic mechanism for each input piston. If the efficiency is 90% for the small piston, what is the AMA? A force of 648 lb on the small piston delivers what force to the ram piston?

18. The handle on the shop press of problems 16 and 17 can travel 25 in. This movement of the handle causes how much movement of the input piston? How far will the ram piston move in one stroke of the handle if the large diameter input piston is used? If the small piston is used?

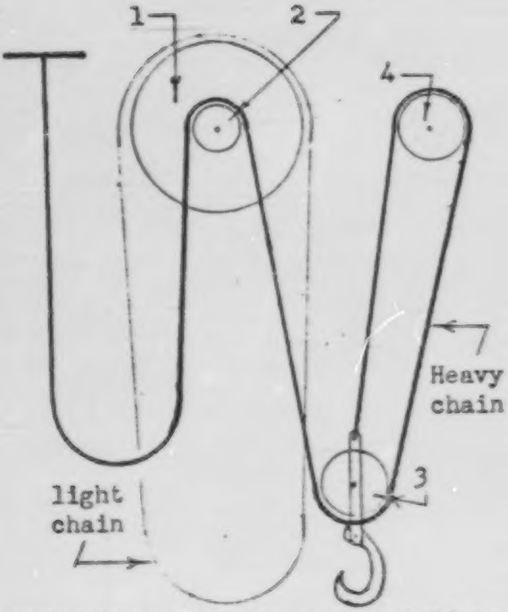
19. What is the overall TMA of the press in problems 16, 17, and 18, using the large input piston? What is the overall efficiency and AMA when the small input piston is engaged? This press has a 100 ton rating (ram force). What input force is required on the handle to achieve this force?

20. The 5.05 in ram (output) pistion of the previous problems is on a 3 in shaft. When the ram is being lifted away from the work, the hydraulic pressure acts on the underside of the piston. Find the overall TMA of the compound machine if the large (input) piston in the pump is used.



21. A small differential pulley is used in a machine shop for lifting heavy equipment. If the two top pulleys have diameters of 14 cm and 13 cm, what is its TMA? If the efficiency is 65%, what input force will lift a 200 lb load?

22.



SHOP HOIST Grooves in the pulleys prevent the heavy chain from slipping.

A hoist in a diesel shop is shown in the accompanying diagram. Pulleys 3 and 4 form a block and tackle, while pulleys 1 and 2 form a wheel and axle. What is the TMA of the block and tackle? What is the TMA of the wheel and axle if the wheel (pulley #1) has a 16 in diameter, and the axle (pulley #2) has a diameter of 3 in? The hoist is operated by the small chain on the wheel (pulley #1). What is the overall TMA of the compound machine?

NOTE: This hoist moves along a beam and the beam can move the length of the shop. Heavy equipment can be moved to any point in the shop.

## ANSWER KEY (PROBLEMS)

## Module M 9 SIMPLE MACHINES

1. Lever: wheel and axle, pulleys, bell crank, gears.
   Inclined Plane: cam, wedge, worm gear, screw.
   Hydraulic Jack: hydraulic lift, hydraulic press, hydraulic pullers.
2. 1st class: pliers, rocker arm
   2nd class: wheelbarrow, nut cracker
   3rd class: tong, forearm
3. TMA $>1$, TMA $<1$
4. No effect, increases, increases
5. Greater the friction, lower the efficiency.
6. $Wki = Wk_o + Wkf$ , $Eff = Wk_o/Wki$
7. 5.9, 7.7
8. 2, 2.25, 3.6, 6
9. 4, 2nd, 26.6 lb
10. 47.7, 53
11. 912 lb, 0.8, 0.72
12. 130, 169, 77%
13. 24.7, 9.35, 231, 12 100 N
14. 12.2
15. 83.5, 83.5
16. 18, 16.2, 684 lb
17. 5, 87.5, 78.8, 51 000 lb
18. 0.28 in, 0.016 in
19. 90, 1275, 81%, 157 lb
20. 10.7
21. 28, 11 lb
22. 3, 5.33, 16

EXPERIMENTS

## Module M 9 SIMPLE MACHINES

PURPOSE: The purpose of these experiments is to study mechanical advantage and efficiency of three simple machines.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing, or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: The equipment for each experiment is listed at the beginning of the procedure section for each experiment. Check to see if it is all available before you start. Ask your instructor if you have questions about the equipment.

PROCEDURE: Experiment 1A "The Wheel and Axle"

Equipment:

1. Wheel and axle (Sargent-Welch #0752)
2. Thread or cord
3. Lab-stand, base and clamps
4. Weight hangers and slotted weights
5. Hooked weights
6. Two meter sticks

1. Assemble the wheel and axle apparatus by clamping it to the upper end of a lab stand.

2. Attach strings or thread to the largest and smallest diameter pulleys. Run the thread through the small hole and make a knot on the other side.

3. Attach a 500 g hooked weight to the thread on the small (output) pulley.

4. Pull the input rope through a distance of seventy-five (75) to one-hundred (100) centimeters and record the amount (input distance).

5. Measure the corresponding distance that the load is lifted (output distance).

6. Calculate the TMA from steps 4 and 5.

7. With a mass of 500 g on the output side of the system, record its weight in dynes.

8. Attach a spring scale to the input rope, Record the force required to lift the load in dynes.

9. Calculate the AMA from steps 7 and 8.

10. Calculate the efficiency from steps 6 and 9.

11. Measure input distance and force required to lift a 1000 g mass through a distance of 10 cm.

12. Calculate the work output from step 11.

13. Calculate the work input from step 11.

14. Calculate the efficiency from steps 12 and 13.

15. Compare steps 10 and 14 by finding the (%) percentage difference.

PROCEDURE: Experiment 1B "The Worm Gear:

Equipment: 1. Worm gear (Sargent-Welch #0795)

On the worm gear apparatus:

1. Count the number of teeth on the large gear.

2. What is the TMA? (line 1)

3. Count the number of revolutions of the worm gear that are needed to cause one complete revolution of the large gear.

4. What is the TMA? (line 3)

5. Compare lines 2 and 4.

PROCEDURE: Experiment 2 "The Screw Jack"

Equipment:
1. Automobile bumper jack (screw-type)
2. 10 lb weight
3. Spring scale
4. Meter stick, ruler, vernier caliper

1. Remove the clip at the bottom of the screw shaft and raise the screw shaft out of the channel. This gives better access for taking measurements.

2. Measure the pitch of the screw (this can usually be done more accurately by measuring the distance of 10 or 20 threads, then dividing).

3. Measure the inside diameter of the screw threads.

4. Measure the outside diameter of the screw threads.

5. Calculate the average diameter from steps 3 and 4.

6. Calculate the TMA of the screw using steps 2 and 5. (See information sheets)

7. Measure the input length of the handle (length of handle from position of hand when using, also see diagram below).

8. Record the output length of the handle. (See diagram below. Assume the fulcrum is the cneter of the shaft. One-half of output force is at A, one-half at B.) Output of handle must equal the average radius of the screw. See step 5.

9. Calculate the TMA of the handle. (From steps 7 and 8)

10. Calculate the overall TMA from steps 6 and 9.

11. Calculate the distance circumscribed by the handle in ten revolutions. (Use step 7.)

12. Measure the movement of the lift bolt in ten revolutions of the handle or calculate it from step 1.

13. Calculate the overall TMA from steps 11 and 12.

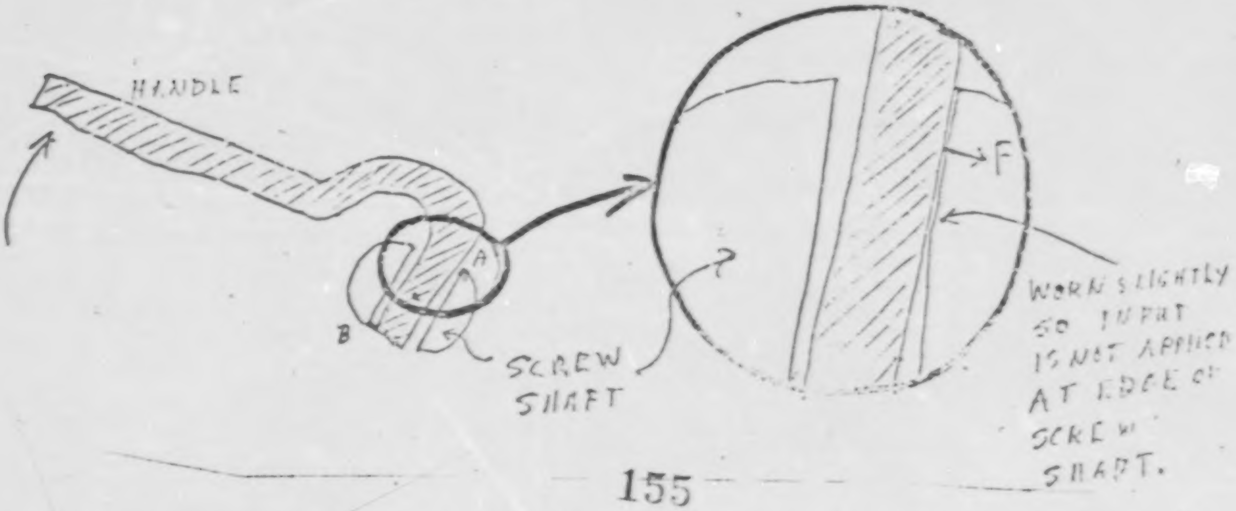
14. Discuss any discrepancy in the calculations of the overall TMA. (Steps 10 and 13)

15. Place a 10 lb weight on the lift bolt and use a spring scale to measure the force required on the handle to lift it. Be sure the weight is lifted vertically. The spring scale should always pull tangent to the handle.

16. What is the overall AMA?

17. Calculate the efficiency of the bumper jack using steps 13 and 16.

18. Does the efficiency seem to be a reasonable value? Explain. What class lever is the handle?


HANDLE
A
B
SCREW SHAFT
?
F
WORN SLIGHTLY SO INPUT IS NOT APPLIED AT EDGE OF SCREW SHAFT.

PROCEDURE: Experiment 3 "The Hydraulic Jack"

Equipment:
1. The hydraulic jack (Sargent-Welch #W1044)
2. Vernier calipers, rulers

CAUTION: The mechanical advantage of the hydraulic jack is quite large. Moderate force on the handle will create pressures in excess of 5000 PSI in the hydraulic fluid. Since the output piston has a cross-sectional area of about 1 in$^2$, the force it can exert is about 5000 lb. DO NOT EXCEED 5000 PSI on the pressure gauge. Damage to the pressure gauge can result.

1. Measure the diameter of the input piston with a vernier caliper.
2. Measure the diameter of the output piston with a vernier caliper.
3. Calculate the TMA using the results of steps 1 and 2.
4. Measure the stroke of the input piston and multiply it by 10. DO NOT DISMANTLE. Use a ruler to measure the movement of the pin.
5. Measure the lift of the output piston in 10 strokes of the input piston.
6. Calculate the TMA using the results of steps 4 and 5.
7. Compare steps 3 and 6 by finding the percentage difference.
8. Measure the input length of the handle from the center of the place where the hand is placed (about 2 in from the end of the handle).
9. What class lever is the handle? Explain.
10. Measure the output length of the handle. DO NOT DISMANTLE. Measure from pin to pin.
11. Calculate the TMA of the lever (handle) from steps 8 and 10.
12. Measure the input stroke of the lever at the center of the place where the hand is placed. This is actually a distance along an arc. Measure as accurately as you can.
13. Calculate the TMA of the lever (handle) using steps 4 and 12. NOTE: The output of the lever equals the input of the hydraulic system.

14. Compare the results of steps 11 and 13 by finding the percentage difference.

15. Calculate the overall TMA from either the average or what you consider the best values of steps 3 and 6 and of steps 11 and 13.

16. Multiply the stroke of the handle (step 12) by 10.

17. Calculate the overall TMA from steps 5 and 16.

18. Compare the results of steps 15 and 17 by finding the percentage difference.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 10

Title: UNIFORM CIRCULAR MOTION

Module Contents:
1. Angular measurement
2. Angular velocity
3. Uniform circular motion
4. Centripetal and centrifugal force
5. Applications

Program: This module was produced especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: This module is an extension of the study of motion to objects traveling in circular paths. This type of motion is frequently encountered in industry and a knowledge of it is necessary for an understanding of the many diverse applications in industry. It is prerequisite to modules on power transmission, harmonic motion, and wave motion. Practical applications are included in the problem sets of this module.

Producer: Gene Waring

Date Produced: November, 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

# STUDENT INSTRUCTIONS

## Module M 10 UNIFORM CIRCULAR MOTION

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. State the definition of the radian as a unit of angular distance, the symbol for angular distance, and the equation for radian measure.
2. State the definition of, and the symbol for, angular velocity.
3. Convert units of angular distance and angular velocity.
4. Distinguish between linear motion along an arc and angular motion associated with circular motion by stating the relationship between linear and angular velocity.
5. Calculate various linear and angular quantities by the use of definitions and relationships stated in objectives 1, 2, and 4.
6. State the formulas for centripetal acceleration and centripetal force in terms of both linear and angular velocity.
7. Apply Newton's three laws of motion to objects in uniform circular motion.
8. Distinguish between centripetal and centrifugal forces in terms of Newton's third law.
9. Solve applied problems in uniform circular motion.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of circular motion. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 7) directs you to the learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 5).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook, plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 8 ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 7, sections 7.1-7.12, pages 173-188.

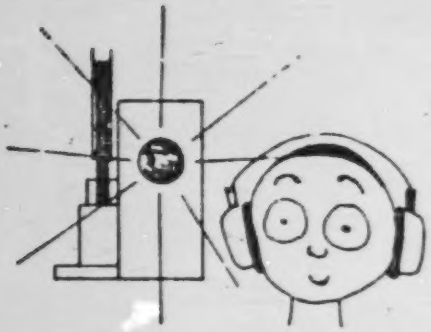
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 9, sections 9.1-9.3, pages 106-108, and chapter 1, section 1.7, page 11, and chapter 11, sections 11.1-11.2, pages 135-137.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall, Inc., 1st ed., 1974. Read chapter 11, sections 11.1, pages 145-147, and 11.3, pages 149-151, and Information Sheet (A-above).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 11, sections 11.1-11.2, pages 140-153.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc. 1st ed., 1966. Read chapter 8, sections 8.1-8.5, pages 105-115, and chapter 11, sections 11.1-11.2, pages 158-160.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Inertial Forces, Centripetal Acceleration, (BFA Ealing 80-2140)

B. Circular Motion, (BFA Ealing 80-3080)

C. Velocity and Acceleration in Circular Motion, (BFA Ealing 80-2546)

III. Report: If you are a student in Electrical, Electromechanical, or Automotive or Diesel Technologies, make a report on how industry has solved problems of overcoming the centripetal forces that act on rotating equipment such as the armature of a DC motor. See instructions on page .

IV. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving circular motion problems. The problems from number five on are applied to your technology.

V. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

VI. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about uniform circular motion.

Read the laboratory instructions in this booklet (yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (M-10) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUVATION TEST

Module M 10 UNIFORM CIRCULAR MOTION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. An object is being whirled in a circle at the end of a string. If the string breaks, centrifugal force will cause it to "fly" radially outward (from the center of the circle).

T - F 2. Angular distance is related to linear (arc) distance by the formula: $s = \theta R$.

T - F 3. A radian is an angle at the center of a circle with an arc length equal to the radius of the circle.

T - F 4. Centripetal and centrifugal forces are an equilibrium pair of forces, act in opposite direction and thus: they cancel each other.

T - F 5. A particle in uniform circular motion has zero acceleration since its linear speed is constant.

6. A motor armature rotates at 1740 rpm. Its angular velocity in radians per second is:

| | |
|---|---|
| a) 10 900 | c) 29 |
| b) 182 | d) 30 300 |

7. A turntable rotates 0.55 revolutions in one second. How far linearly does the needle "travel" in one second? The groove is 15 cm from the center of the record. (Answer in centimeters)

| | |
|---|---|
| a) 25.9 | c) 51.8 |
| b) 104 | d) 8.25 |

8. A pulley drives a V-belt at a surface speed of 15 ft/s. If the pulley has a 2 in radius, what is its angular velocity in radians per second?

| | |
|---|---|
| a) 45 | c) 30 |
| b) 7.5 | d) 90 |

9. A small segment of wire conductor on the outer edge of a motor armature has a mass of 2.83 g. It is 10 cm from and lays parallel to the axis. Find the centripetal force on the wire segment if the motor rotates at 1720 rpm.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 10 UNIFORM CIRCULAR MOTION

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. F | I. Reading or II. Listening/Viewing |
| 2. T | I. Reading |
| 3. T | I. Reading |
| 4. F | I. Reading or III. Solving Problems |
| 5. F | I. Reading or III. Solving Problems |
| 6. b | III. Solving Problems or V. Lab Experiment |
| 7. c | III. Solving Problems or V. Lab Experiment |
| 8. d | III. Solving Problems or V. Lab Experiment |
| 9. 918 000 dynes<br>9.18 N | III. Solving Problems or V. Lab Experiment |

INFORMATION SHEET

Module M 10 UNIFORM CIRCULAR MOTION

## ANGULAR MEASUREMENT

In the measurement of angles in triangles and other polygons, the angles are less than one revolution and many times are less than a right angle. Measurement of such angles are usually made in units of degrees. When many revolutions occur in a short time in rotating equipment, the angular measurement is counted in revolutions or radians.

The number of revolutions an object turns is the number of complete rotations it makes. The radian is defined by the following formula:

$$\theta = \frac{s}{R} \qquad 1.$$

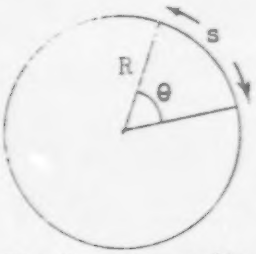


Fig 1. The radian.

where s is the arc subtended by the angle and R is the radius. The symbol θ is the greek letter theta. Refer to figure 1. Notice that when the arc distance is equal to the radius, the angle is one radian. There are $2\pi$, or about 6.28 radians in one revolution. One radian is about 57.3°.

The arc distance and the radius must be measured in the same units. The units of the angle, therefore, are ft/ft, m/m, mi/mi, etc. The units cancel! The radian is just a name for this size of an angle. It doesn't act like other units do. If it is mixed in with other units, we can substitute ft/ft for it and cancel, effectively dropping it out.

EXAMPLE: A pendulum swings through an angle of 0.35 rad. Its length (radians) is 2.5 m. Through what arc length does the pendulum bob swing?

GIVEN: $\theta = 0.35$ rad

$R = 2.5$ m

SOLUTION: $s = \theta R = (0.35 \text{ rad})(2.5 \text{ m}) = (0.35 \text{ m/m})(2.5 \text{ m})$

$= 0.88$ m

Radians are simply dropped from the answer. Notice, since the radius is known, the swing of the pendulum in the example above is completely described by giving the angle (0.35 rad), an angular quantity. A complete description is also given when the arc distance (0.88 m), a linear quantity, is known.

## ANGULAR VELOCITY

Since the position of an object moving in circular motion can be described by either linear or angular quantities, the velocity of the motion can also be described by linear or angular quantities. An electron going around the nucleus of an atom, a car going around a curve and a rope or chain unwinding off a pulley can best be described by the linear velocity ($v$) in ft/s or m/s of the object. However, the rotation of drive shafts, flywheels, gears and motor armatures, are better described by the angular velocity ($\omega$) measured in rad/s or rpm.

Angular velocity is defined by the formula:

$$\omega = \Theta/t \qquad 2.$$

The symbol ($\omega$) is the greek letter omega (small case). Since there are $2\pi$ rad in one revolution and 60 s in one minute, then:

$$1 \text{ rad/s} = 2\pi/60 \text{ rpm}$$

EXAMPLE: Find the angle in radians that a flywheel turns through in 0.5 s if it is turning at 3000 rpm.

GIVEN: $t = 0.5$ s

$\omega = 3000$ rpm $= 314$ rad/s

SOLUTION: $\Theta = \omega t = (314 \text{ rad/s})(0.5 \text{ s}) = 157 \text{ rad}$

## LINEAR AND ANGULAR RELATIONSHIPS

The relationship between linear distance ($s$) and angular distance ($\Theta$) is given by equation 1. If this formula is rearranged it becomes:

$$s = \Theta R$$

If both sides are divided by time, the left side becomes the linear velocity and the right is the angular velocity times the radius:

$$v = \omega R \qquad 3.$$

This formula provides the relationship between linear velocity and angular velocity. Angular velocity must be expressed in rad/s in this formula.

EXAMPLE: What is the linear speed of a point on the edge of the flywheel in the previous example if its radius is 40 cm? What linear distance does it turn in 0.5 s?

GIVEN: $t = 0.5$ s

$\theta = 157$ rad

$R = 40$ cm $= 0.4$ m

$\omega = 314$ rad/s

SOLUTION: $v = \omega R = (314 \text{ rad/s})(0.4 \text{ m}) = 126$ m/s

$s = \theta r = (157 \text{ rad})(0.4 \text{ m}) = 62.8$ m

## CIRCULAR MOTION

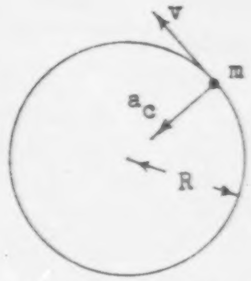


Fig 2. Circular motion.

When an object moves around in a circular path at a constant linear (or angular) velocity, it is traveling in uniform circular motion. Suppose the object has a mass m (see figure 2) and a linear velocity v in an object of radius R. The magnitude of the velocity will not change. Its direction, however, is changing constantly, always tangent to the curve. Notice the direction of the velocity at the instant shown. Suppose this is a mass swinging on the end of string. If the string should break at this instant, what direction would the object go? Since it is going in the direction of v, it would continue going in that direction. Its inertia would prevent it from going in any other direction since there are no external forces on it after the string breaks.

Newton's first law determines the direction the object will go if the string breaks. It also states that if the object is to follow a path other than a straight line, if it's going to follow the curved path, there must be an external force acting on it. It's easy to see that the force must be down and to the left at the instant shown (figure 2) if it is to curve downward away from a straight line path.

Newton's second law states what the magnitude of that force will be: $F = ma$. Many textbooks show how the acceleration is determined and its direction. The derivation is not repeated here. It has a magnitude of:

$$a_c = v^2/R \qquad 4.$$

and is a centripetal acceleration, meaning it is in a direction toward the center of rotation. In terms of the angular velocity it is:

$$a_c = \omega^2 R \qquad 4\text{ a.}$$

This formula is found by combining formulas 3 and 4 and simplifying.

EXAMPLE: A child sits 5 ft from the center of a merry-go-round rotating at 30 rpm. What is her linear velocity and acceleration? Check with both equations: 4 and 4a.

GIVEN: $R = 5$ ft

$\omega = 30$ rpm $= 3.14$ rad/s

SOLUTION: $v = \omega R = (3.14 \text{ rad/s})(5 \text{ ft}) = 15.7 \text{ ft/s}$

$a_c = \omega^2 R = (3.14 \text{ rad/s})^2 (5 \text{ ft}) = 49.4 \text{ ft/s}^2$

$a_c = \omega^2 / R = (15.7 \text{ ft/s})^2 (5 \text{ ft}) = 49.4 \text{ ft/s}^2$

The acceleration is very large because the angular velocity of the merry-go-round is very high. The child's inertia must be overcome so she holds on tightly to a cross bar. Her tendency to move in a straight line exerts an outward force (centrifugal) on the bar, bending it slightly. The bar exerts a reaction force on the child set up by its elasticity. This is an inward or centripetal force on the child. The friction between the child and the seat contributes some of the centripetal force, also.

The outward force (centrifugal) is a force on the parts of the merry-go-round and not on the child. The centrifugal force does not affect the child's motion. It is simply a reaction to the centripetal force required to cause her to move in circular motion. Newton's third law describes such action-reaction pairs of forces.

## CENTRIPETAL FORCE

The magnitude of the force on a rotating object is found by substituting the formulas for centripetal force into Newton's second law:

$$F_c = \frac{mv^2}{R} \qquad 5.$$

or:

$$F_c = m\omega^2 R \qquad 5\text{ a.}$$

Remember that mass is found by dividing weight by the acceleration of gravity.

EXAMPLE: In order for the child (in the previous example) to keep from falling off the merry-go-round, what centripetal force is required? She weighs 50 lb.

GIVEN: $w = 50$ lb

$m = w/g = 50 \text{ lb}/(32 \text{ ft/s}^2) = 1.56$ slug

$v = 15.7$ ft/s

$w = 3.14$ rad/s

$R = 5$ ft

SOLUTION: $$F_c = \frac{mv^2}{R} = \frac{(1.56 \text{ lb s/ft}^2)(15.7 \text{ ft/s})^2}{5 \text{ ft}} = 76.9 \text{ lb}$$

or: $$F_c = m\,w^2R = (1.56 \text{ lb s}^2/\text{ft})(3.14 \text{ rad/s})^2(5 \text{ ft}) = 76.9 \text{ lb}$$

The merry-go-round is turning very rapidly, the child must exert a force greater than her own weight. If friction between her and the seat is not substantial, she may have difficulty holding on at such a high speed.

Numerous applications of the centripetal force formulas are included in your text.

WORK

In the absence of friction, an object in uniform circular motion would continue forever. The centripetal force is perpendicular to the direction of motion at any instant. Recall the formula for work: $Wk = Fs \cos \theta$. In uniform circular motion, the angle ($\theta$) between the direction of force and the direction of movement is always 90°. The cosine of 90° is zero. So, no work is done by centripetal forces.

No work is done by a uniform magnetic field in deflecting a beam of electrons. An electron orbits the nucleus of an atom in a friction free environment. The moon orbits the earth. The earth orbits the sun. If there were no friction, the moon and the earth would orbit forever. Since friction is small (tides) the orbiting of the moon will continue for a long, long time.

Work is done only when the angular speed changes. Tangential forces are required ($\theta \neq 0$) to speed up or to slow down a rotating object.

PROBLEMS

## Module M 10 UNIFORM CIRCULAR MOTION

1. Does the centripetal force do any work on an object in uniform circular motion? Explain your answer.

2. What force causes circular motion? What is the reaction of this force?

3. Explain the difference between linear (arc) distance and angular distance. Between linear velocity and angular velocity.

4. Why is the radian measure of angles the same for all measuring systems?

5. An electric motor is held down with four bolts. If you observe the motor from one end, the shaft turns clockwise. Is the force on all four bolts the same? Explain.

6. Express the following angles in radians: 30°, 45°, 60°, 90°.

7. Express the following angles in degrees: $\pi$ rad, $\pi/6$ rad, $\pi/4$ rad, $\pi/3$ rad, $\pi/2$ rad, 0.28 rad, 0.73 rad.

8. Recommended cutting speed on a lathe for aluminum is 300 ft/min. What is this speed in ft/s? If the work piece has a 1 in diameter, at what angular velocity should the lathe be turning in radians per second? At what rpm should the lathe be set?

9. A lathe is set to run at 200 rpm while turning a 2 in low-carbon steel workpiece. What is the angular speed in radians per second? The cutting tool takes off a continuous ribbon of metal. At what speed does the ribbon leave the surface of the workpiece (cutting speed)? How many feet of the ribbon will be removed in 10 min?

10. A V-belt pulley on a lathe has a diameter of 3 in. It rotates at 1775 rpm. In 3 s, it rotates through what angular distance in radians? What length of V-belt runs over the pulley in 3 s?

11. One hundred twenty centimeters of V-belt rolled over a pulley. If the pulley has a 14 cm diameter, what angle did it turn through?

12. If the V-belt of problem 11 has a surface speed of 1.2 m/s, what is the angular velocity of the pulley?

13. A straight grinding wheel (with high strength bonding) has a 10 in diameter. The standard maximum surface speed is 6500 ft/min. At what maximum angular speed should this wheel be run in radians per second? In rpm?

14. Reinforced grinding wheels manufactured with high strength organic bonding may operate at up to 5425 rpm. How many radians per second is this? What is the surface speed of a 10 in wheel in ft/s? In ft/min?

15. If the grinding wheel described in problem 13 were operated at the speed of the one in problem 14, it would probably disintegrate and fly apart. If a small one ounce piece of the wheel was originally located with its center 4.5 in from the axis, what centripetal force would have been necessary to hold it in place? What is the linear speed of this piece in miles per hour at the instant the wheel breaks up? The angular speed is 5425 rpm. Assume it does not collide with other pieces.

16. A Bridgeport vertical mill has a cutter with a carbide tip attached. The center of the carbide tip is 1.2 in from the axis of rotation. If the tip weighs 0.15 oz, what is the greatest centripetal force the adhesive must produce to hold it? The greatest angular velocity of the mill is 2720 rpm. Would you expect this force to be greater than or less than the force exerted on the tip by the object being milled?

17. A Milwaukee vertical mill has its cutters mounted 5.5 cm from the axis of rotation on the cutting head. The mill is being used to cut aluminum at a surface cutting speed of 2000 ft/min. What is the angular speed of the cutter in rad/s? In rpm? What is the centripetal force that must be provided by the three hold-down screws on the cutter insert? It has a mass of 42 g. (Be careful with mixed units!)

ANSWER KEY (PROBLEMS)

Module M 10 UNIFORM CIRCULAR MOTION

1. No, $\theta = o$, $F \perp s$
2. Centripetal, centrifugal
3. Hint: s and $\theta$, v and $\omega$
4. Arc and radius measured in same units which cancel
5. Force on left bolts due to reaction forces when armature accelerates. Force on right bolts at constant speed due to friction.
6. 0.52, 0.79, 1.05, 1.57
7. 180, 30, 45, 60, 90, 16, 41.8
8. 5, 120, 1150
9. 20.9, 1.75 ft/s, 1047
10. 558, 69.7 ft
11. 17.1 rad
12. 17.1 rad/s
13. 260 rad/s, 2480 rpm
14. 568 rad/s, 237 ft/s, 14 200 ft/m
15. 236 lb, 145 mi/h
16. 2.38 lb, less
17. 185 rad/s, 1764 rpm, 78.8 N

REPORT

## Module M 10 UNIFORM CIRCULAR MOTION

The following brief report should be completed by students in Electrical, Electromechanical, Automotive, and Diesel Technologies.

A segment of winding on the armature of a DC motor is about 4 in long. It lies in a slot in the laminated core, about 2 or 3 inches from the axis of rotation. In a large motor, it may be of 14 gauge copper wire. Such a motor operates at about 1750 rpm without a load. The segment of wire requires several pounds of centripetal force to keep it in its orbit about the axis. A number of such wires lay in the slots to complete the armature windings.

Naturally, the wire can move outward from the axis, only by taking up slack in the windings or by stretching the wires. Disintegration of the wires would begin if any of the armature parts move outward enough to catch on the stator parts. Great care must be taken to insure that this does not happen. Special problems arise in the construction of the commutator.

Look up in various technical books to find out more about the equipment and methods used to overcome the problems of holding an armature together. Write a short report (two or three paragraphs) describing cord bands, wire bands, glass tape bands, slots and wedges, and varnish and how they are used. Try to observe each of these on various armatures in the shop. (Your technical instructors may be able to show you cut-away models, etc.) One complete paragraph of the report should be devoted to the special problems associated with the commutator.

R. Rosenberg, Electric Motor Repair, Holt-Reinhart-Winston, 1960.

D. Braymer and A. Roe, Rewinding Small Motors, 3rd ed., McGraw-Hill, 1949.

K. Graham, Understanding and Servicing Fractional Horsepower Motors, American Technical Society, 1964.

C. Veinott, Fractional and Subfractional Horsepower Electric Motors, 3rd ed., McGraw-Hill, 1970.

EXPERIMENT

## Module M 10 UNIFORM CIRCULAR MOTION

PURPOSE: The purpose of this experiment is to study circular motion. You will measure the centripetal force, angular velocity, radius, and mass of a rotating object. You will then test the formula for centripetal force that relates these quantities.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: Check to see if all the following equipment is available before you start.

1. Centripetal force apparatus (Spring balance type) Sargent-Welsh #0932.
2. Stop clock, (electric) 1/10 second.
3. Harvard trip balance (metric)
4. Meter stick

PROCEDURE: This experiment requires two people working together; one to swing the object in a circle and read the spring balance; the other to time a counted number of revolutions.

CAUTION: Examine the cord to make certain it is in good condition. Make sure it is well secured to the rubber stopper and to the spring scale. Frequent examination of the nylon cord will prevent the damage or injury that could occur if the rubber stopper should fly off through the lab. Ask your instructor if there is any doubt.

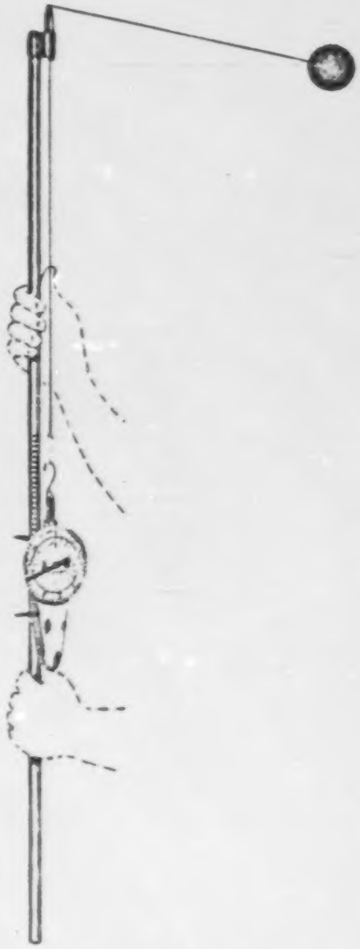
CAUTION: When the rubber stopper is being whirled around in a circle, do not rotate any faster than is necessary to cause the spring balance to read full scale. To do so will put too much strain on the nylon cord and could cause it to break.

1. Observe the stop clock. Notice that it can be operated by a remote switch when the toggle switch. (upper right) is in the off position. One revolution of the large hand is ten seconds. Six revolutions of the large hand is one minute.

2. Adjust the spring balance by sliding it up and down the rod so the cord length from rod tip to rubber stopper is about one-half meter.

3. One person should now practice rotating the rubber stopper above his head in a horizontal circle. (See figure) After a little practice, you will be able to rotate the apparatus at constant velocity. Constant velocity rotation is apparent when the spring scale remains steady. Best results are obtained if the spring scale reading is between 1.5 N and 2.5 N.

NOTE: Your hands should be held as shown in the figure. To prevent the tip of the rod from rotating in a large circle, one hand should be closer to the tip than the figure shows. Hold the apparatus so your fingers do not touch the string.



Centripetal force apparatus*

4. At the same time one person is practicing with the apparatus, the other should practice timing. Start the clock when the rubber stopper is moving toward you. When the clock is started, count "zero." Count "one" when stopper is moving toward you the next time around. Count "two" on the following cyle, etc. Stop the clock at the end of 15 revolutions.

NOTE: For an accurate timing, the clock will have to be started after the other person has the apparatus rotating at constant speed. He should indicate to the timer when he is ready.

5. You are now ready to take readings with the apparatus.

6. Set the clock on zero.

7. When the person rotating the rubber stopper says "start," measure the time for 15 revolutions.

NOTE: If the spring scale should indicate unsteady speed during a measurement, stop the timing and begin again.

* By permission from Sargent-Welch Scientific Company, Instructions for the use of # 0932 Centripetal Force apparatus.

8. Record the following measurements on the data sheet:

   A. The time for 15 revolutions.
   B. Spring balance reading.
   C. Radius of the swing. (Measure from the tip of the rod to the center of the rubber stopper. Pull the rubber stopper out until the spring balance reads the same as it did during the other measurements.)

9. From step 8A, calculate the angular velocity ($\omega$) in rad/s.

10. Use the formula for centripetal force ($F = m\omega^2 R$) to calculate the mass of the rubber stopper.

11. Reset the apparatus so the distance from rod tip to rubber stopper is about 0.75 m.

12. Repeat steps 6 through 10 at the new setting. Exchange jobs for this measurement. Record data and calculations on the data sheet.

13. Reset the apparatus so the distance from rop tip to rubber stopper is 1 m.

14. Repeat steps 6 through 10 at the new setting after exchanging jobs again. Record on data sheet.

15. Calculate the average mass from the three calculated values.

16. Measure the mass of the rubber stopper on the Harvard trip balance. (Measurement with the spring balance by turning it upside down will not be accurate. Why?)

17. Compare the calculated value of the mass with the measured value. $\left(\frac{\text{meas - calc}}{\text{meas}} \times 100\%\right)$

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE — Milford Campus
Milford, Nebr. 68405

Module: M 11

Title: POWER TRANSMISSION

Module Contents:
1. Rotational dynamics
2. Gears and pulleys
3. Torque and power transmission
4. Torque and power measurement

Program: This module has been prepared especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to study the efficiency with which rotating equipment transmits the energy produced by motors and engines. In rotating machines, the transmission of energy is accompanied by changes in torque and angular speed. (Changes in force and linear speed occurred in the simple machines of module M 9.) The study of gears and pulleys, torque and power measurement are included. Manufacturing technicians must have some knowledge of the rotating equipment that is used so extensively in industry.

Producer: Gene Waring

Date Produced: November, 1975

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## Module M 11 POWER TRANSMISSION

### OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define angular velocity and angular acceleration. State the defining formulas and the units of each.
2. Define torque, horsepower and the units of each in both British and MKS systems.
3. Define speed ratio and efficiency. State the formulas for each for various gears or pulleys, including compound arrangements.
4. State the relationship between angular velocity and linear velocity.
5. State Newton's second law for rotation and the formulas for kinetic energy of rotation for a disc or ring.
6. State the formulas for power under steady velocity (linear or angular) conditions.
7. Describe the difference between spur, helical, bevel, herringbone, and worm gears.
8. Describe a pinion and gear, rack and pinion.
9. Describe the difference between a spur gear acting on an internal ring gear, and between a spur gear acting on an external ring gear.
10. Describe the purpose of an idler gear.
11. Calculate various problems using the formulas in objectives one through six.
12. State the formula for brake horsepower and solve various problems involving the Prony brake.
13. Describe the brake system, the cooling system, and the transducer system which provides the read out of horsepower or torque and angular speed of various dynamometers.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

### SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of power transmission. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 7 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 8 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 6 ).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 9 ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 6, sections 6.28-6.31, pages 162-169 and chapter 8 (all) pages 206-222.

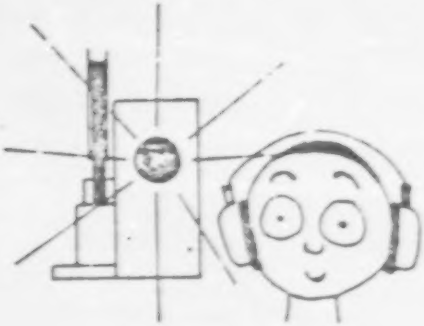
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 11, sections 11.1-11.7, pages 135-142, and chapter 7, section 7.10, page 87.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 11, pages 145-155 and all of chapter 12, pages 156-173.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 11, sections 11.2-11.4, pages 149-164; and chapter 12, pages 181-182; and chapter 8, section 8.2, pages 95-98.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 11, sections 11.1-11.7, pages 156-170 and chapter 9, sections 9.3-9.4, pages 130-132; and chapter 12, sections 12.6-12.7, pages 183-188.

II. Listening/Viewing: The following single concept film loop (8 mm) is available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the film. Ask the LRC personnel about this training.



A. Simple Machine: the gear, (EBE S-80831)

III. Outside Reading:

Flywheels, Post, R.F., Post, S.F., Scientific American, Volume 229, Number Six, December, 1973; pages 17-23.

This article describes the advances in mechanical design and materials used to manufacture flywheels. These advances make it possible to use giant flywheels to store energy in electric-power systems and smaller ones for the propulsion of cars, trucks, and buses.

This magazine is available in the Learning Resource Center.

IV. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page 19 ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving torque and power problems. The problems from number five on are applied to your technology.

V. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

VI. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about how power is measured in rotating equipment.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given.) Obtain a laboratory data sheet (M-11) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

VII. Guided Tour: Ask your instructor to arrange for a guided tour of the dynamometers in use in the shops on the Milford Campus. He will schedule a day when most of the students in your class can go along. Stops on the tour include:

| LOCATION | POWER MEASURED | LOADING SYSTEM | COOLING SYSTEM | SIZE |
|---|---|---|---|---|
| Basic Mechanics | Engine Output | Water Turbine Brake | Water Cooled | Portable |
| Diesel Shop | PTO Output | Oil Turbine Brake | Water Cooled | Portable |
| | Engine Output | Water Turbine Brake | Water Cooled | Large |
| Automotive Shop | Rear Wheel | Water Turbine Brake | Water Cooled | Under Floor |
| | Brake System | Water Turbine Brake | Water Cooled | Motor Driven |
| | Transmission Loss | Disc Brake | Air Cooled | Engine Driven |
| Electrical Shop | Armature Shaft | Disc Brake | Air Cooled | Small (Motors) |
| | Armature Shaft | Electric Generator Brake | Air Cooled | Medium |
| | Armature Shaft | Magnetic Brake | Air Cooled | Large |

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

## Module M 11 POWER TRANSMISSION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Angular acceleration and centripetal acceleration are two names for the same quantity.

T - F 2. The moment of inertia of an object depends on how its mass is distributed relative to the axis of rotation.

T - F 3. When one spur gear drives another, the driver gear is called a pinion and the driven gear is a ring gear.

T - F 4. A pinion with 7 teeth will rotate four times faster than the ring gear it drives with 28 teeth.

T - F 5. One horsepower equals 33 000 watts.

6. A force of 28 lb is applied to a torque wrench with a handle 18 in long. The torque is:

a) 504 lb ft
b) 42 lb ft
c) 18.7 lb ft
d) 1.56 lb ft

7. What power is developed by a small electric motor turning at 1750 rpm if the torque is 0.5 m N?

a) 91.6 W
b) 875 W
c) 367 W
d) 36.7 W

8. The torque ratio of a pair of spur gears is 9. The efficiency is 90%, what is the speed ratio?

a) 1
b) 0.11
c) 8.1
d) 10

9. A flywheel is in the form of a disc 40 cm in diameter. Its mass is 20 kg. How much rotational kinetic energy does it have if it is rotating at 50 rad/s?

10. A small electric motor is being tested by a Prony brake. The pulley has a diameter of 1.125 in. The spring scales read 34.5 oz and 2.5 oz when the motor speed is 1775 rpm. Find the brake horsepower under this load.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 11 POWER TRANSMISSION

| Question-Answer | If you missed this question, you are directed to these learning activities: |
|---|---|
| 1. F | I. Reading |
| 2. T | I. Reading or IV. Solving Problems |
| 3. F | I. Reading |
| 4. T | I. Reading or II. Listening/Viewing and IV. Solving Problems |
| 5. F | I. Reading or VI. Experiments |
| 6. b | I. Reading or IV. Solving Problems or III. Outside Reading |
| 7. a | IV. Solving Problems and VII. Tour |
| 8. d | IV. Solving Problems |
| 9. 500 J | IV. Solving Problems and III. Outside Reading |
| 10. 0.032 hp | VI. Experiment or IV. Solving Problems |

INFORMATION SHEET

## Module M 11 POWER TRANSMISSION

Module M 10 (Circular Motion) described rotational motion when the speed was not changing. Angular accelerations are produced by torques in much the same way linear accelerations are produced by forces (Newton's 2nd law).

Forces can create torques about the axis of rotation if the force has a tangential component. Centripetal forces are radial so they produce no torque since there is no lever arm. Centripetal forces are necessary for an object to go in a circle but create no tendency to change the angular speed.

To illustrate these points, suppose you were on a bicycle. Your feet are on the ground and you hold the front wheel off the ground by lifting the handle bars. A friend spins the front wheel to a high speed. Except for a small amount of friction in the bearing, the wheel continues to rotate with no tendency to speed up or slow down.

Lowering the bicycle to the ground sets up frictional forces between the tire and ground; a force tangent to the tire. On gravel roads, the wheel kicks gravel back toward your feet. On hard-top roads, the same tendency exists; a backward force on the road. The reaction to the force on the road is a forward force on the bicycle. The frictional force is tangent to the wheel and slows it down. Pedaling the bicycle or stepping on the brakes causes similar angular accelerations on the wheels. Accompanying the angular acceleration of the wheels is the linear propulsion or braking of the bicycle by the road through the medium of friction. On ice or when the drive wheels are elevated, the wheels spin but the propulsive force is lacking because a tangent force is lacking.

Since friction is involved between the road and tires (and in bearings), work must be done to maintain speed. The torque and power required to maintain constant speed or to accelerate must be transmitted from the pedals to the tire by a "power train" (gears and chain). In the case of automobiles and trucks, power is transmitted from the engine through a number of gears and drive shafts. In other rotating equipment, V-belt pulleys are used.

The discussion that follows includes the subjects of rotational dynamics, gears and pulleys, and power measurement.

### ROTATIONAL DYNAMICS

Angular distance ($\theta$) and angular velocity ($\omega$) were defined in module M 10, but are repeated here for easy reference.

$$\theta = s/R \quad (\text{rad}) \qquad 1.$$

$$\omega = \theta/t \quad (\text{rad/s}) \qquad 2.$$

The relationship between linear velocity and angular velocity is:

$$v = \omega R \qquad 3.$$

Angular acceleration ($\alpha$) is defined by the following formula:

$$\alpha = \frac{\omega - \omega_0}{t} \quad (\mathrm{rad/s^2}) \qquad 4.$$

Where $\omega$ is the final angular velocity and $\omega_0$ is the initial angular velocity.

EXAMPLE: A certain phonograph turntable (33 1/3 rpm) reaches full speed in 0.0942 s. What is the angular acceleration both in $\mathrm{rad/s^2}$ and $\mathrm{rev/s^2}$?

GIVEN:

$\omega_0 = 0$

$\omega = 33\ 1/3$ rpm $= 3.49$ rad/s

$t = 0.0942$ s

SOLUTION:

$$\alpha = \frac{3.49\ \mathrm{rad/s} - 0}{0.0942\ \mathrm{s}} = 37.1\ \mathrm{rad/s^2}$$

$$= 9.50\mathrm{rev/s^2}$$

Torque (T) is defined as force times the lever arm (see module M4). Lever arm is defined as the perpendicular distance from the fulcrum (axis of rotation) to the line of action of the force. Since the forces on rotating equipment are nearly always tangential, the lever arm is the distance from the axis to the point where the force is applied (radius). The formula for torque then is:

$$T = FR \qquad 5.$$

Its units are lb·ft or N·m.

Notice that the units have the same combination as work and energy units. They are not the same, however, and work units are usually distinguished by reversing the order: ft·lb or m·N = J. Technically, work is a scalar quantity; torque is a vector. They are not the same quantity even though torque and energy are both transmitted by rotating equipment. Movement is required if work is to be accomplished; torques can be applied with or without movement (rotation). A torque can be applied to a head bolt on an automobile engine with a torque wrench, for example. Work is being done as long as the bolt turns. However, the wrench handle could be turned to apply a torque to a tightened bolt, then wired in that position to the fender. The wrench could be left like that for five years and no work would be done, but a torque would be applied to the bolt throughout the entire time.

When an externally applied net torque is applied to a piece of rotating equipment, it will cause an angular acceleration. Newton's second law states that a net force causes a linear acceleration (F = ma). Newton's second law for rotation is very similar but the angular acceleration depends on how the mass is distributed. A given torque will accelerate a given mass at a greater acceleration if the mass is in the form of a disc rather than a hoop. In a hoop, the mass is concentrated around the outer rim; in a disc, it is not. In a hoop, the entire mass is going at the same speed; in the disc, it is not.

Newton's second law for rotation is in the form:

$$T = I\alpha \qquad 6.$$

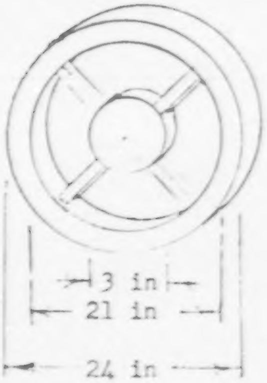
where I is called the moment of inertia. The moment of inertia depends on the distribution of mass within the rotating object. Formulas for the moment of inertia for a few simple objects are:

Table 1

| Diagram | Object | Moment of Inertia |
|---|---|---|
| | Disc or solid shaft | $I = \frac{1}{2}MR^2$ |
| | Hoop or pipe | $I = MR^2$ |
| | Thin Rod | $I = 1/3\ ML^2$ |

EXAMPLE:

Fig 1



A flywheel has the shape shown in figure 1; a hoop connected to a hub by four spokes. The hoop weighs 100 lb, each spoke is 9 lb, and the hub (disc) is 15 lb. Find the angular acceleration of the flywheel when 80 lb·ft of torque is applied. Note: A force of 80 lb applied along the outer rim by a rope would produce this torque.

The moment of inertia of a compound arrangement like this is the sum of that for each part. The spokes present a special problem since they are not rotating about the end. Imagine they extend to the center. If they did, they would weigh 10.5 lb and would be 10.5 in long. The moment of inertia for the spokes can be calculated by the formula in table 1 for a thin rod. Then subtracting that for the imaginary part.

GIVEN: (Spokes) $Mi = {}^{W}/g = 10.5\ lb/32\ ft/s^2 = 0.328$ slug

$Mi = 1.5/32 = 0.047$ slug (Imaginary part)

$R = 10.5$ in $= 0.875$ ft

$Ri = 1.5$ in $= 0.125$ ft (Imaginary part)

$I = 1/3\ MR^2 - 1/3\ Mi \cdot Ri^2$

$= 0.0837$ slug ft$^2$ $- 0.00002$ slug ft$^2$

$= 0.0835$ slug ft$^2$ (each spoke)

GIVEN: (hub) $M = 0.469$ slug

$R = 1.5$ in $= 0.125$ ft

$I = 1/2\ MR^2 = 0.0037$ slug ft$^2$

GIVEN: (hoop) $M = 3.125$ slug

$R = 11.25$ in $= 0.938$ ft (average)

$I = MR^2 = 2.7495$ slug ft$^2$

GIVEN: $I$ total $= 4(0.0835) + 0.0037 + 2.7495 = 3.09$ slug ft$^2$

$T = 80$ lb ft

SOLUTION: $\alpha = \frac{T}{I} = \frac{80 \text{ lb ft}}{3.09 \text{ slug ft}^2} = 26.0 \text{ rad/s}^2$

Notice that almost all the moment of inertia is in the outer rim. The hub could have been ignored, completely, and the spokes contributed only about 8%.

The kinetic energy of rotation also depends on the distribution of mass in a rotating object:

$$E_R = \tfrac{1}{2} I \omega^2 \qquad 7.$$

EXAMPLE: Find the rotational kinetic energy of the flywheel in the previous problem if it is rotating at an angular speed of 1200 rpm.

GIVEN: $\omega = 1200$ rpm $= 126$ rad/s

$I = 3.09$ slug$\cdot$ft$^2$

SOLUTION: $E_R = \tfrac{1}{2} I \omega = \tfrac{1}{2}(3.09 \text{ slug ft}^2)(126 \text{ rad/s})^2$

$= 24\ 500$ ft lb

Power is transmitted against a constant resisting torque in much the same way as it is against a constant force of friction ($P=fv$).

$$P = T\omega \qquad 8.$$

This formula is important in the measure of torque or power when rotational motion is involved. Most power measuring devices (dynamometers) consist of a tachometer along with a meter that reads either power or torque. The other quantity can easily be calculated with equation 8.

Work done by a torque is the product of the torque and the angle turned through in radians:

$$W_k = T\Theta \qquad 9.$$

GEARS AND PULLEYS

Gears and pulleys are used to transmit rotational motion and, at the same time increase or decrease torque and speed. Spur gears and pinions transmit power to an axis parallel to the drive axis (see figure 2). The smaller of two mesned gears is called the pinion. If the larger gear is quite a bit larger, it is usually called a ring gear. Notice that spur gears have the teeth parallel to the axis.

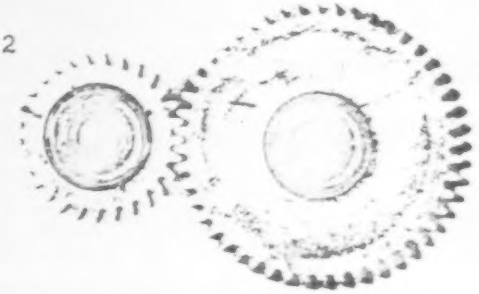


Fig 2

A helical gear and pinion accomplish the same purpose as spur gears. The teeth are set at an angle to the axis on the surface of a disc (see figure 3). The point of contact between teeth on helical gears slides along the tooth. This makes helical gears run quieter than spur gears. Helical gears are stronger since more teeth are meshed at all times.

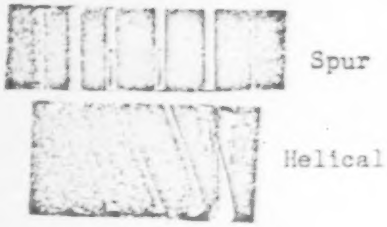


Fig 3

A beveled gear and pinion transmits power to an axis prependicular to the drive axis (see figure 4). The teeth are on the surface of a section of cone.

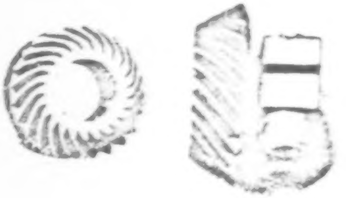


Fig 4

A ring gear and worm (figure 5) does the same thing as a beveled gear, transmitting power at right angles to the drive axis. Worm gears are usually used when greater mechanical advantage is needed. Power is not readily transmitted backward from ring gear to worm unless they are specially designed. Worm gears are less efficient because the teeth slide continually on the worm (inclined plane). Worm gears have been used in automobile and truck differentials instead of a ring gear and pinion.

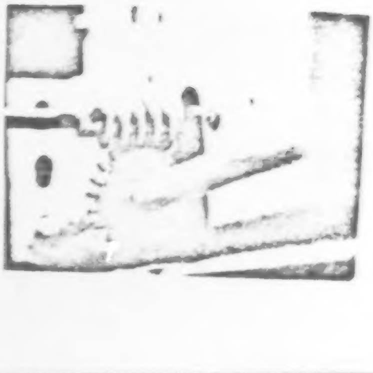


Fig 5

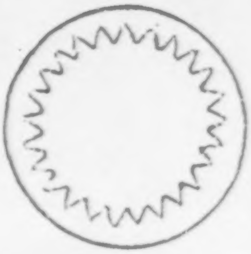


Fig 6

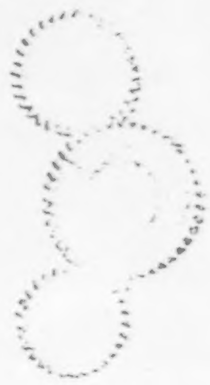


Fig 7

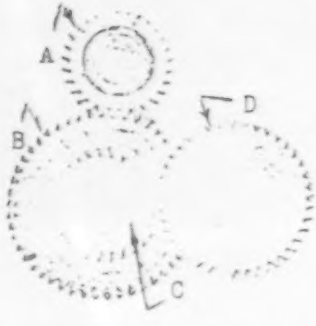


Fig 8

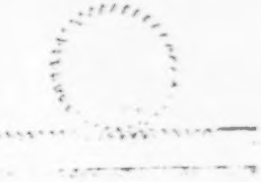


Fig 9

Fig 10

Spur and helical ring gears turn the opposite direction to the pinion if the teeth are external as in figures 2 and 3. An internal ring gear (figure 6) turns the same direction as the pinion.

Two spur gears will run the same direction, if they are in mesh with an idler gear (figure 7). If the two spur gears are the same size, there will be no mechanical advantage no matter what the size of the idler.

Figure 8 shows two sets of ring gears and pinion. Gear A drives gear B. Gear B and C are keyed or welded to the same shaft. Gear C drives gear D. Speed reduction occurs at the AB and CD combinations but not the BC combination. Gears B and C form a wheel and axle arrangement and rotate at the same angular speed.

Figure 9 shows a pinion running on a linear track called a rack. This combination is called a rack and pinion and transforms angular motion to linear motion. Either the rack or the pinion can be stationery. The pinion is attached to the carriage on a lathe, for example. The carriage moves along the rack. Pulleys connected by V-belts rotate the same direction (see figure 10). A twist in the belt will reverse the direction. Idler pulleys are used to create the proper tension in the belt.

## SPEED RATIO

In the study of simple machines (Module M9), the important consideration was mechanical advantage. The multiplication (or reduction) of forces and linear motion was the prevailing concept. Forces applied to one tooth by another are not multiplied. Only action-reaction forces (Newton's third law) are acting when two teeth are in contact. The movement of one tooth forward on one gear causes one tooth to move on the other no matter what the size of the gears are.

Since the equal forces are applied at different distances from the axis when two different sized gears are in mesh, the torque may be multiplied or reduced. Angular speeds will also be different. It is the changes in torque and angular speed that is important in transmission of rotating motion by gears and pulleys.

The torque ratio (TR) is similar to the AMA of other simple machines:

$$TR = \frac{T_o}{T_i} \qquad 10.$$

The speed ratio (SR) (sometimes called speed reduction ratio or speed multiplication ratio if inverted) is similar to the TMA and is based on the geometry of the particular gears and pulleys. It is defined as the angular speed of the input gear to that of the output gear:

$$SR = \frac{\omega_i}{\omega_o} \qquad 11.$$

If the speed ratio is greater than 1, the gears or pulleys reduce the angular speed but torque is increased. It is a multiplication of angular speed if the speed ratio is less than 1 and torque is reduced.

The speed ratio is usually easier to find using geometric measurements rather than angular speeds. For pulleys:

$$SR = \frac{d_o}{d_i} \qquad 12.$$

Where $d_i$ and $d_o$ are the diameters of the input and output pulleys, respectively.

Using the ratio of the number of teeth (n) on a pair of gears is the easiest and most accurate method:

$$SR = \frac{n_o}{n_i} \qquad 13.$$

Efficiency is the ratio of the torque ratio to speed ratio:

$$Eff = \frac{TR}{SR} \qquad 14.$$

This is similar to the ratio of AMA to TMA of module M9 on simple machines.

EXAMPLE: A simple spur ring gear and pinion have a speed ratio of 6. If the pinion has 9 teeth, how many does the ring have? If the efficiency is 75%, what is the torque ratio? The pinion has an input of 24 lb·ft of torque. What is the output torque of the ring? If the pinion is turning at 900 rpm, how fast is the ring turning?

GIVEN: $SR = 6$

$Eff = 75\%$

$n_i = 9$

$T_i = 24$ lb ft

$\omega i = 900$ rpm

SOLUTION: $n_o = (6)(9) = 54$ teeth equation 13.

$TR = (0.75)(6) = 4.5$ equation 14.

$T_o = (24 \text{ lb ft})(4.5) = 108$ lb ft equation 10.

$\omega_o = \frac{900 \text{ rpm}}{6} = 150$ rpm equation 11.

The solution to the problem can be checked by calculating the work accomplished in one minute.

CHECK: $Wk_o = T_o\theta_o = (108 \text{ lb}\cdot\text{ft})(2\pi(150)\text{rad} = 101\ 800 \text{ ft}\cdot\text{lb}$ equation 9.

$Wki = Ti\theta i = (24 \text{ lb ft})(2\pi)(900) \text{ rad} = 135\ 700 \text{ ft}\cdot\text{lb}$ equation 9.

$Eff = Wk_o/Wki = 75\%$

The check could have been made as easily using equation 8 for power and the formula: $Eff = P_o/Pi$.

The total speed ratio of combination of gears (or pulleys) such as shown in figure 8 is found by multiplying the speed ratios at each point where gears mesh.

$$SR_T = (SR_{AB})(SR_{BC})(SR_{CD})\ .\ .\ . \qquad 15.$$

EXAMPLE: Find the speed ratio of the combination of gears in figure 8 if gear A has 7 teeth, gear B has 24 teeth, gear C has 9 teeth, and gear D has 30 teeth. Gear A is the input. If the angular speed of gear A is 1000 rpm, what is the speed of gear D?

GIVEN: $n_A = 7$

$n_B = 24$

$n_C = 9$

$n_D = 30$

$\omega_A = 1000$ rpm

SOLUTION: $SR_{AB} = 24/7 = 3.43$

$SR_{BC} = 1$ (wheel and axle)

$SR_{CD} = 30/9 = 3.33$

$SR_T = (3.43)(1)(3.33) = 11.42$

Gear D rotates 11.42 times slower so:

$$\omega_D = \frac{1000\ \text{rpm}}{11.42} = 87.6\ \text{rpm}$$

## POWER MEASUREMENT

Power is the rate at which work is done. Work is the result of a force acting through a distance or a torque acting through an angle. An engine or an electric motor must exert a torque through an angle for a period of time if it is to produce power. The angle and time are easily measured by using a tachometer to get the angular speed.

To measure the torque of a shaft rotating at high speed requires special equipment. The torque must be transferred to a stationery device so it can be measured. The device is called a dynamometer and consists of one of various kinds of brakes. The torque applied to the brake is transmitted to a read-out device (meter) calibrated to read force, torque, or horsepower. The brake can be set to load the motor or engine by any amount desired. The braking system may be a cradled electric generator, a water turbine, a magnetic (eddy current) brake or a friction brake. The read-out device may be simple spring scales, hanging weights, hydraulic pressure gauges, load cells, or strain gauges.

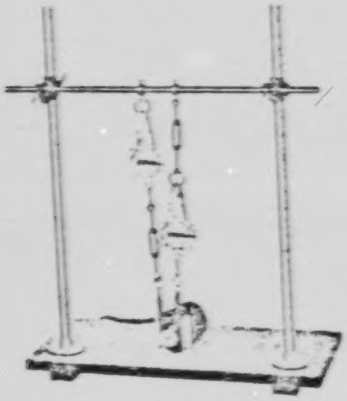


Fig 11 By permission from
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## PRONY BRAKE

The experiment that accompanies this module uses a simple Prony brake. A belt slides on a drum or pulley on the end of a motor shaft. Friction applies a braking torque to the motor. It increases the tension in the belt (see figure 11) on the right side and relieves tension on the left. Friction is measured by the difference in the spring scale readings. Friction applies a torque to the motor tangent to the drum or pulley. The lever arm is the radius of the drum. Angular speed is measured with a tachometer.

Equation 8 gives the formula for power. If the spring scale readings are in pounds, radius in feet and angular speed in rpm the formula (in horsepower) becomes:

$$P = \frac{2\pi R(T_2-T_1)(\text{rpm})}{33\,000} \qquad 16.$$

If the spring scale readings are in grams, radius in centimeters and angular speed in rpm equation 8 (in watts) becomes:

$$P = \frac{2\pi R(T_2 - T_1)(980)(\text{rpm})}{60 \times 10^7} \qquad 16a$$

The 980 converts grams (mass) to dynes (force). The 60 converts rpm to rps and the $10^7$ converts erg/s to watts. More information about the Prony brake is included in the instructions for the experiment in this module (yellow pages).

DYNAMOMETERS

Dynamometers are power or torque measuring devices that have built-in tachometers. In fact, a dynamometer has other built-in equipment which usually enables a person to read the power or torque directly from a meter. If the meter reads one quantity, the other can be quickly calculated using equation 8.

The dynamometer converts the rotational torque to a stationery torque by using various kinds of brake systems. The brake system absorbs the energy transmitted to it from the engine or motor. Those dynamometers designed for continuous use are usually water-cooled. Air-cooled dynamometers are for intermittent use only.

Various dynamometers are in everyday use on the Milford Campus. They are used to measure the power or torque right off the engine or motor shaft. Some measure the power delivered to a power-take-off shaft on tractors. Others measure the power delivered to the rim of the rear tires on automobiles. One measures the torque delivered to the wheels by the brakes on an automobile. These are motor driven. One measures the loss of power and torque as energy is transmitted through an automobile transmission.

There is much to be learned by actually seeing the various kinds of equipment utilized in these dynamometers. Go on the tour when it is scheduled. (See learning activity number VII ).

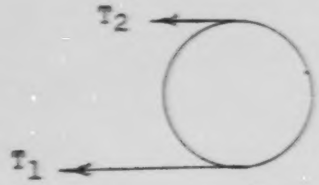
PROBLEMS

Module M 11 POWER TRANSMISSION

1. Define work and torque. In what ways do the two quantities differ? How are units of work distinguished from units of torque?

2. What are some advantages of using helical gears instead of spur gears? Which is easier to manufacture?

3. What are some advantages of using beveled ring gears and pinions instead of a ring gear and worm? Look up in reference books to find out what a hypoid ring gear and pinion is.

4. 

A V-belt runs over a pulley as shown in the diagram where $T_1$ is greater than $T_2$. If the pulley drives the belt, which way is the pulley turning? If the belt drives the pulley?

5. The work done on a rotating object is the torque times the angle (in radians) that it turns through. How is the input work, output work, and the work done against friction related?

6. How is the power output of an automobile engine, the power output of the transmission, and the power losses within the transmission related?

7. A flywheel in the form of a disc has the same mass and radius as one in the form of a ring (spokes and hub have negligible moment of inertia). If the same torque was applied to each, which one will accelerate faster? Explain. If both flywheels were rotating at the same angular speed, which one has the most rotational kinetic energy? Explain.

8. A Lodge and Shipley 16 inch Lathe has a spindle weighing 14.2 lb. It is in the form of a pipe with an average diameter of 2.125 in. The chuck can be considered as two solid cylinders molded in one piece. One part has a diameter of 12 in the other 7 in. The large part weighs 108 lb; the smaller weighs 26 lb. Find the moment of inertia of each part and the total. A 1.875 in hole in the center of the chuck can be neglected. Note: The chuck is attached to the spindle.

9. Maximum operating spindle speed on the lathe in problem 8 is 1080 rpm. Suppose the lathe was started with the spindle in gear with no workpiece attached. If 22 lb ft of torque is applied to the spindle, how much time would it take to accelerate to maximum speed? Minimum spindle speed is 36 rpm and 662 lb ft of torque is applied to the spindle. How much time is required to attain minimum operating speed? The moment of inertia of the spindle-chuck combination is 1.134 slug $ft^2$.

10. From the information given in problem 9, find the rotational kinetic energy of the spindle-chuck combination at maximum speed and at minimum speed.

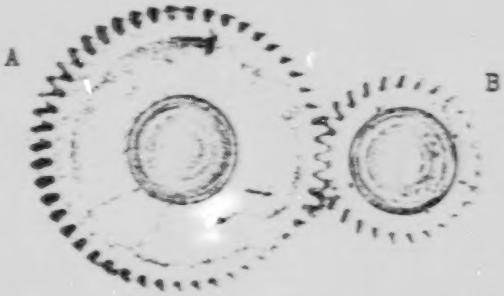
11. The electric motor driving the lathe in the previous problem is rated at 5 hp (normal load) and operates at 1740 rpm. What torque does it produce? If the motor efficiency is 84%, what input power in watts is required? What power does the motor produce at maximum load if the torque is 33.7 lb ft and angular speed is 1640 rpm?

12. What is the speed ratio of the gear and pulley train connecting the drive motor and spindle when the spindle speed is maximum (1080 rpm)? The motor speed is 1740 rpm. What is the speed ratio at minimum spindle speed (36 rpm)? What is the torque ratio of the gears and pulleys for each speed if the efficiency is 49%? If the torque produced by the motor is 28 lb ft, what torque is applied to the spindle at each speed?

13. The flywheel on a punch press consists of a hub, six spokes and a large ring all molded together. The masses of each part are 30.9 kg (hub), 2.3 kg (each spoke) and 88.9 kg (ring). The hub has a radius of 9.5 cm and is in the form of a solid cylinder. The spokes are 16.5 cm long and are in the form of thin rods. The ring has an average radius of 29.9 cm. Find the moment of inertia of each part and the total. See the example problem in the Information Sheets of this module.

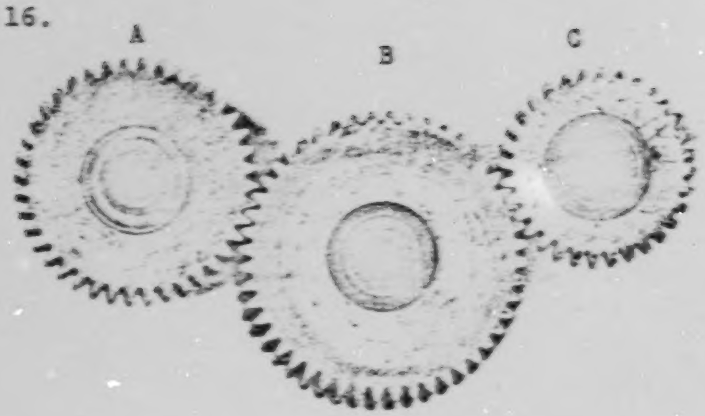
14. The flywheel on the punch press described in problem 13 has a total moment of inertia of 8.62 kg m$^2$. The drive motor runs at 880 rpm. A 10 cm pulley on the motor drive shaft drives the flywheel with a V-belt around its outer edge, a diameter of 66 cm. At what speed does the flywheel run and how much rotational kinetic energy does it have? If the motor delivers 12 N m of torque at normal load and the V-belt is 80% efficient, find the torque the V-belt delivers to the flywheel.

15.



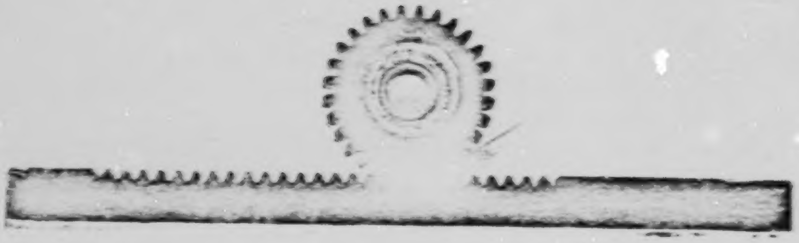
If gear A is the driver and is rotating at 1200 rpm, how fast is gear B turning? Gear A has 40 teeth, and gear B has 32 teeth. What is the speed ratio?

16.



If gear A is the driver, and is rotating at 800 rpm, how fast is gear C rotating? Gear B is an idler. What direction does gear C rotate if gear A rotates clockwise? Gear A has 32 teeth, B has 40, and C has 28. What is the speed ratio? What is the speed ratio if gear C is the driver?

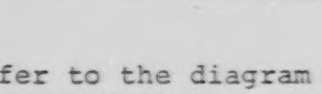
17.



If the spur gear has 48 teeth and is 3.4 cm in diameter, and is rotating 3 rpm, how much time is required to rotate one-half revolution? The movable rack has 26 teeth in a length of 6.2 cm. How far will it move in one-half revolution of the gear? At what speed does it move? If the gear rotates clockwise, what direction does the rack move?

18. A worm gear rotates at 140 rpm. What angular speed does the ring gear it drives rotate if it has 45 teeth?

19.



A 3 in pulley on a motor drives a squirel-cage furnace fan with an 8 in pulley. What is the speed ratio for this V-belt system? If the motor turns at 1720 rpm, what speed is the fan rotating?

20. Refer to the diagram in problem 4. If the pulley diameter is 12 cm and it is rotating at 2000 rpm, what power is being transmitted by the pulley? $T_1$ is 60 N and $T_2$ is 15 N.

21. Refer to the diagram in problem 4. If the pulley diameter is 3.5 in and is rotating at 1250 rpm, what horsepower is being transmitted to the pulley by the V-belts? $T_1$ is 90 lb and $T_2$ is 40 lb.

22. Refer to figure 8 in the information sheets of this module. Gear A with 28 teeth drives gear B (49 teeth). Gear C has 32 teeth and drives gear D (40 teeth). What is the overall speed ratio? If gear A rotates at 1000 rpm, what is the angular speed of gear D? If gear A delivers a torque of 50 lb ft and the efficiency of the system is 75%, what torque is delivered to gear D?

23. A one-third horsepower motor operates at 1720 rpm. What torque does it deliver?

24. A one-fourth horsepower electric motor operates at 1700 rpm. The motor drives a gear reduction box. The output shaft of the gear reduction box rotates at 85 rpm. The gear reduction box is 60% efficient. With what net force can the machine pull a V-belt on a 3 inch pulley on the output shaft? What is the speed ratio of the gear box?

25. What torque can the force in the V-belt in problem 24 deliver to a 1 ft diameter pulley?

ANSWER KEY (PROBLEMS)

Module M 11 POWER TRANSMISSION

1. Work is force time distance moved, torque is force times lever arm. Work is a scalar, movement must take place. Torque is a vector, movement (rotation) may or may not occur. ft lb-lb ft, etc.

2. Quieter and stronger. spur.

3. Force can easily be transmitted both directions.

4. ccw, cw

5. Wki = Wko + Wkf

6. Engine output equals transmission input. Pi = Po + Pf

7. Disc. $T = I\alpha$. If I is less $\alpha$ is greater. Ring. $E_R = \frac{1}{2}I\omega^2$. I is greater.

8.

| | |
|---|---|
| spindle | 0.014 slug $ft^2$ |
| large cylinder | 0.844 slug $ft^2$ |
| small cylinder | 0.276 slug $ft^2$ |
| total | 1.134 slug $ft^2$ |

9. 3.87 s, 0.0065 s

10. 7250 ft lb, 2.14 ft lb

11. 15.1 lb ft, 4440 W, 10.5 hp

12. 1.61, 48.3, 0.79, 23.7, 22 lb ft, 662 lb ft

13.

| | |
|---|---|
| hub | 0.18 kg $m^2$ |
| six spokes | 0.49 kg $m^2$ |
| ring | 7.95 kg $m^2$ |
| total | 8.62 kg $m^2$ |

14. 133 rpm, 840 J, 63.4 N m

15. 1500 rpm, 0.8

16. 914 rpm, cw, 0.88, 1.14

17. 10 s, 4.8cm/s, left

18. 3.11 rpm

19. 2.67, 645 rpm

20. 565 W

21. 1.74 hp

22. 2.19, 457 rpm, 82 lb ft

23. 1.02 lb ft

24. 31 lb, 20

25. 15.5 lb ft

EXPERIMENT

## Module M 11 POWER TRANSMISSION

### The Prony Brake

PURPOSE: The purpose of this experiment is to study the operation of the Prony brake and to determine the horsepower and efficiency under various loads.

CAUTIONS:

1. Read all of the instructions before handling any of the equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using.
3. Observe all cautions listed in the procedure section of these instructions.

INFORMATION: The Prony brake is a device for measuring the power output of an engine or motor. Power is defined as the rate of doing work. In equation form:

$$P = \frac{Wk}{t} \qquad 1.$$

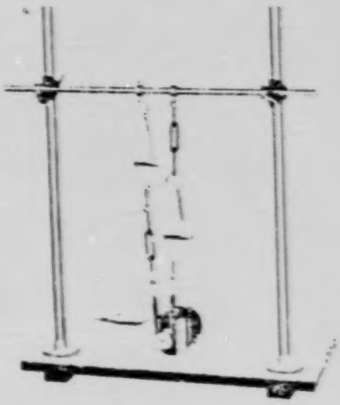
where work is the product of a force applied, times the distance through which it acts.

The Prony brake has a belt that passes around a pulley or drum mounted on the output shaft of a motor. Each end of the belt is fastened to a spring scale. When the belt is tightened on the pulley, friction develops as the pulley turns. The frictional force drags the belt around relieving tension on the left side, increasing it on the right (see figure 1). The frictional force being overcome on the periphery of the pulley is the difference between the scale readings. The work being done against friction is the product of the frictional force times the distance through which it is applied. In one revolution of the pulley, the distance is circumference of the pulley - $\pi$ d - where (d) is the pulley diameter:

$Wk = (F_1 - F_2)\pi d$ for one revolution.

For a number of revolutions, say N revolutions:

$Wk = (F_1 - F_2)\pi dN$



By permission Sargent-Welch Scientific Company. Cat # 1067C

Since power is the rate of doing work (equation 1), we can use revolutions per second (rps):

$$P = (F_1 - F_2)\pi d(rps)$$

Since the power input is measured in watts, the output should also be measured in watts for easy calculation of efficiency. If the scale readings are in kilograms and the diameter of the pulley is measured in meters:

$$P(watts) = (F_1 - F_2)(9.81)\pi d(rps) \qquad 2.$$

where 9.81 is the acceleration of gravity in mks units.

Efficiency is the ratio of output over input:

$$Eff = \frac{P_o}{P_i} \; 100\% \qquad 3.$$

The efficiency of a motor is usually maximum at rated loads and less for loads either under or over rated load.

EQUIPMENT: Check to see that all the following equipment is available before you start. Ask your instructor if you have any questions about the equipment.

1. (1) one Sargent-Welch Prony brake, Cat. #4227-40
2. (2) two Spring scales (2000 oz capacity)
3. (1) one Leather belt
4. (2) two Turnbuckles
5. (1) one Wattmeter (0 to 1000 watts)
6. (1) one Tachometer
7. Vernier caliper
8. Various electrical connectors

PROCEDURE:

1. Use a vernier-caliper to measure the pulley diameter in centimeters. Record on the data sheet in centimeters and meters both.
2. Attach a turnbuckle to each scale and then hang each scale from hooks on the horizontal support rod. (See figure 1.)
3. Attach the belt to one turnbuckle, run it around the pulley, and then attach it to the other turnbuckle. The natural (not tanned) side of the belt should be against the pulley.

4. Position the horizontal support rod with the turnbuckles fully extended, as high as possible without putting a load on the scales.

5. Connect the motor lead to the load side of the wattmeter, the 5 amp terminal. Connect the wall plug to line terminals A and B of the wattmeter.

CAUTION: This motor is designed for intermittant use only as it will heat up rapidly after you turn it on in the next step. In addition, heat is produced by friction on the pulley and is conducted along the armature shaft to add to the problem. Take all readings as quickly as you can; then, turn the motor off.

CAUTION: Hold the tachometer, gently, with the rubber tip against the end of the motor shaft (in the next step). Slippage must not occur but excessive pressure will give a faulty reading by applying a load to the motor. The shaft of the tachometer must be parallel to the motor shaft for accurate readings.

6. With both scales reading zero, turn the motor on and measure the rpm with the tachometer. Record the rpm, scale readings and the wattmeter reading in line (1) one of table (1) one on the data sheet. TURN THE MOTOR OFF AS QUICKLY AS POSSIBLE.

7. Calculate the output power in watts, torque in Newton meters, and the efficiency and record in table (1) one. Do this before the next trial to let the motor cool as much as possible. This becomes more important after the first few trials.

8. Turn the motor on and adjust the turnbuckles to increase the load (as read on scale $F_1$) to 200 g. (See figure 1) Quickly read the tachometer, both scales and the wattmeter. TURN THE MOTOR OFF. Record data in table (1) one and calculate the output power, torque, and efficiency before the next trial as the motor cools.

9. Repeat step 8 to complete trials 3 through 10, increasing the load (on scale $F_1$) by 200 g each time. Make adjustments and record data as quickly as possible and shut the motor off between trials. Calculate the power output, torque and efficiency each time to let the motor cool between trials.

10. On the graph paper provided, plot rpm horizontally. Plot output power, torque and efficiency vertically on the same graph. Use colored pens for the curves for easy identification.

11. Disassemble the equipment and return to storage.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: M 12

Title: SIMPLE HARMONIC MOTION

Module Contents:

1. Hooke's law
2. Displacement and amplitude
3. Period and frequency
4. Simple harmonic motion
5. Velocity and acceleration
6. Force and energy

Program: This module was produced especially for students in:

1. Electrical technology
2. Electronic service technology
3. Electronic engineering technology
4. Electronmechanical technology

Purpose: The purpose of this module is to study vibratory motion in its simplest form: simple harmonic motion (SHM). Harmonic motion and wave motion have several essential similarities. In both, the motion repeats itself at regular intervals and in both the motions represent the conversion of potential energy to kinetic energy and back, continuously. This module is prerequisite for modules on wave motion. In addition, numerous applications of SHM can be found in electrical and electronic technologies.

Producer: Gene Waring

Date Produced: April 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

## Module M 12 SIMPLE HARMONIC MOTION

### OBJECTIVES

When you have satisfactorily completed this module you will be able to:

1. Define SHM, amplitude, frequency, angular frequency, period, displacement and equilibrium points, as these quantities relate to simple harmonic motion.

2. State the formulas for the period of a mass on a spring and for the simple pendulum.

3. State the relationships between angular frequency and frequency and between frequency and period.

4. State the formulas for velocity and acceleration as a function of displacement and the formulas for the maximum values of these quantities.

5. Describe the phase relationships between displacement, velocity and acceleration in SHM by being able to state at what part of the vibrations the maximum values of these quantities occur.

6. Given the equation for the displacement, state the amplitude and angular frequency and calculate the frequency and period of the vibration.

7. Calculate the displacement, velocity and acceleration given the equation for displacement and the maximum values of velocity and acceleration.

8. State the relationship between kinetic, potential and total energy in a vibrating system by an equation and by stating at what part of the vibration the energy is all kinetic and at what parts it is all potential.

9. State the formula for the total energy of a vibrating system as a function of frequency, amplitude and mass.

10. Solve various problems using the definitions, laws and formulas described in objectives 2,3,4,5,6,7,8 and 9.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of SHM. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowlege of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions, correctly. The answer key page (pink paper, also) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowlege of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in some of the textbooks.

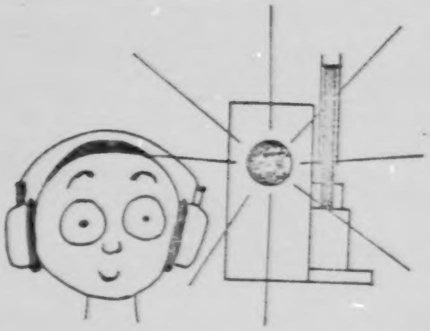
B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read part of chapter 18, sections 18.1-18.6, pages 491-502.

C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read part of chapter 10, sections 10.1-10.7 pages 121-127.

D. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read part of chapter 17, sections 17.1-17.3, pages 286-297.

E. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read all of chapter 15, pages 228-238.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Simple Harmonic Motion: The Reference Circle (ISBN-0-03-080164-8)

B. The Wilberforce Pendulum BFA Ealing 80-2157 (QA/865/W63X)

C. Simple Harmonic Motion (BFA Ealing 80-3098)

D. Simple Harmonic Motion: The Stringless Pendulum (BFA Ealing 80-2785)(QC/122/M462X/#9)

E. Center-of-Mass Pendulum (BFA Ealing 80-2793)(QC/122/M462X/#1)

F. Velocity and Acceleration in Simple Harmonic Motion (BFA Ealing 80-2553)(QC/231/V49X/#4)

G. Velocity in Circular and Simple Harmonic Motion (BFA Ealing 80-2520)(QC/231/V49X/#5

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving simple harmonic motion problems. The problems from number five on are applied to your technology.

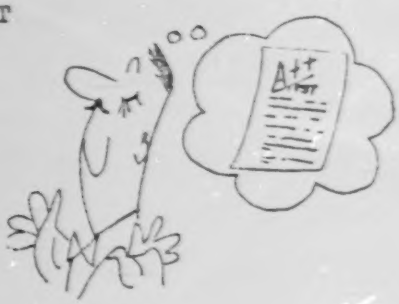
IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are two experiments in this module. They will give you practice in learning about harmonic motion.

Read the laboratory instructions in this booklet (on yellow paper) and pay particular attention to the cautions given. Obtain a laboratory data sheet (M 12) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

The instructions for a third experiment are included. You may perform this experiment if you wish, it is optional.

## TEST



You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module M 12 SIMPLE HARMONIC MOTION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. A radian is an angle at the center of a circle whose arc length is equal to the diameter of the circle.

T - F 2. The energy content of a mass on a spring is continuously being exchanged between kinetic energy and elastic potential energy.

T - F 3. In simple harmonic motion, the period is independent of the amplitude.

T - F 4. The maximum speed in simple harmonic motion depends on the frequency.

T - F 5. The amplitude of a body undergoing simple harmonic motion is its total range of motion.

6. An object undergoes SHM with an amplitude of 5 cm. Its velocity is zero when its displacement is:

a) zero
c) 5 cm
b) 2.5 cm
d) 10 cm

7. A simple pendulum is 1 m long. ($g = 9.80\ m/s^2$). Its period is:

a) 2.01 s
c) 1 s
b) 0.64 s
d) none of these

8. If $y = 4 \sin 180\pi t$ is the equation of an object vibrating in SHM, find the period.

a) 90 s
c) 0.011 s
b) 180 s
d) 0.0056 s

9. What is the total energy of an object vibrating in SHM if its mass is 0.5 kg? The frequency is 2 Hz and the amplitude is 2 cm.

OVER

10. An object vibrating in SHM has an amplitude of 2 cm. Its period is 1/20 s. Write the equation for displacement as a function of time. (t = 0 at the equilibrium point).

ANSWER KEY TO THE SELF-EVALUATION TEST

Module M 12 SIMPLE HARMONIC MOTION

| Question-Answer | | If you missed this question, you are directed to these learning activities |
|---|---|---|
| 1. | F | I Reading |
| 2. | T | I Reading |
| 3. | T | I Reading |
| 4. | T | I Reading or III Solving Problems |
| 5. | F | I Reading |
| 6. | c | III Solving Problems |
| 7. | a | III Solving Problems |
| 8. | c | III Solving Problems |
| 9. | 0.0158 J or 158 000 erg | III Solving Problems or V Experiments |
| 10. | $y = 2 \sin 40\pi t$ | III Solving Problems |

INFORMATION SHEET

Module M 12 SIMPLE HARMONIC MOTION

Simple harmonic motion (SHM) (sometimes called sinusoidal motion) is a vibratory or back and forth motion in which the acceleration is proportional to but in the opposite direction to the displacement. Formulas for the displacement, velocity and acceleration are derived from circular motion using a reference circle.

In the module on circular motion (M 10) you studied the definition of angular velocity:

$$\omega = \theta/t \qquad 1.$$

Which is measured in radians per second. In simple harmonic motion, the quantity is called angular frequency instead of angular velocity since there is no angular motion in the straight back and forth motion of SHM. Formulas for displacement, velocity and acceleration have the angle $\theta$ replaced with the product $\omega t$. See equation 1. These quantities are , therefore, expressed as functions of time rather than angles.

Relations between angular motion and linear motion were also studied in module M 10 such as the formula:

$$v = \omega R \qquad 2.$$

relating the linear velocity to the angular velocity and the formula:

$$a = \omega^2 R \qquad 3.$$

relating linear acceleration to angular acceleration. The letter R represents the radius of the circle.

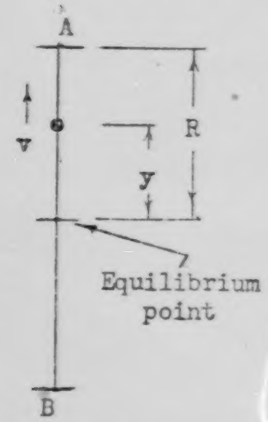


Fig 1 SHM

When an object vibrates in SHM, several quantities are important:

Equilibrium Point. The equilibrium point is the position at which the vibrating object will eventually come to rest. (See figure 1) Imagine the path shown (between A and B) is the path of a mass on the end of a spring bouncing up and down. It will eventually come to rest in the center.

Displacement. The displacement (y) of an object vibrating in SHM is the distance it is from the equilibrium point. (See figure 1) The displacement is usually positive above the equilibrium point and negative when the object is below it. The velocity is positive when moving in an upward direction regardless of its location.

Acceleration is negative when the object is above the equilibrium point and positive below regardless of the direction of movement.

Amplitude. The amplitude (R) is the maximum value of the displacement. Notice that it is one-half the total swing and not the distance from one end of the swing to the other.

Period. The period (T) is the time for the object to complete one cycl of the vibration.

Cycle. A cycle is one complete performance of the vibration.

Frequency. The frequency (f) is the number of cycles per unit of time usually expressed in cycles per second (Hertz). Frequency is the reciprocal of the period:

$$f = \frac{1}{T} \qquad 4.$$

Angular frequency. The angular frequency ($\omega$) is the number of radians per unit of time (radians per second). Angular frequency is $2\pi$ times the frequency. It is sometimes expressed in $\pi$-radians per second:

$$\omega = 2\pi f \qquad 5.$$

Time. The time (t) is measured on the clock. It is a variable. Be sure to distinguish it from the period which is constant. (Capital T is the period; lower case t is the variable time).

DISPLACEMENT, VELOCITY AND ACCELERATION

Formulas for displacement, velocity and acceleration are derived in your textbook from a reference circle. They are listed here for convenience:

$$y = R \sin \omega t \qquad 6.$$

$$v = \omega R \cos \omega t \qquad 7.$$

$$a = -\omega^2 R \sin \omega t \qquad 8.$$

Formulas for velocity and acceleration as a function of displacement are usually easier to use if the displacement has already been calculated or is known:

$$v = \omega \sqrt{R^2 - y^2} \qquad 9.$$

$$a = -\omega^2 y \qquad 10.$$

The maximum values of velocity and acceleration are:

$$v(\max) = \omega R \qquad 11.$$

$$a(\max) = -\omega^2 R$$

Notice (comparing equations 11 and 9) that the maximum velocity occurs when the displacement is zero (at the equilibrium point). Comparing equations 12 and 10, you can see that the maximum acceleration occurs when the displacement is maximum ($y = R$).

## THE SHM EQUATION

A given simple harmonic motion can be described in a very simple way using the equation for displacement (equation 6). This formula is seldom used to actually find the displacement at a given time (although, it can be). Usually, it is used as a shorthand description of the specific motion of an object vibrating in SHM.

EXAMPLE: The equation for the motion of a mass on a spring is given by: $y = 4 \sin 10\pi t$ (cm - s). Find the amplitude, angular frequency, frequency, period, maximum velocity and maximum acceleration.

Solution: Compare the equation here with equation 6.

$R = 4$ cm (amplitude)

$\omega = 10\pi$ rad/s (angular frequency)

$f = 5$ Hz (equation 5)

$T = 0.2$ s (equation 4)

$v(\text{max}) = 126$ cm/s (equation 11)

$a(\text{max}) = 3950$ cm/s$^2$ (equation 12)

EXAMPLE: Find the displacement,velocity and acceleration at the end of 0.01 s.

Solution:

$$y = 4 \sin \left[10\pi(0.01) \text{ rad}\right]$$

$$= 4 \sin (0.31 \text{ rad})$$

$$= 1.24 \text{ cm}$$

$$v = 10\pi \sqrt{4^2 - 1.24^2} \quad \text{(equation 9)}$$

$$= 119 \text{ cm/s}$$

$$a = -(10\ )^2\ (1.24) \quad \text{(equation 10)}$$

$$= -1220 \text{ cm/s}^2$$

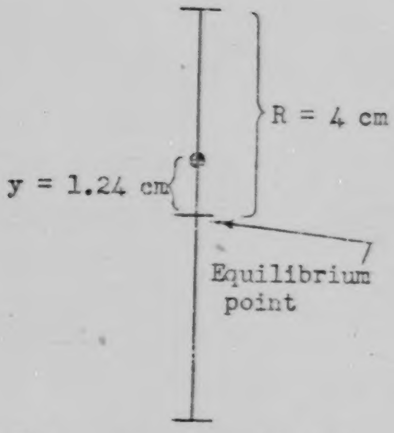


Fig 2 Displacement and amplitude

The mass is 1.24 cm above the equilibrium point (see accompanying diagram). It is moving upward at 119 cm/s. When it passed through the equilibrium point it was traveling at 126 cm/s. It is decelerating at 1220 cm/s$^2$. The deceleration will increase to 3950 $cm/s^2$ when it gets to the top of the swing where the speed will be zero.

## MASS ON A SPRING

If equations 4 and 5 are substituted into equation 10 and solved for the period, the following equation is obtained:

$$T = 2\pi\sqrt{-\frac{y}{a}} \qquad 13.$$

Where y is the displacement and a is the acceleration. One of these quantities will be negative and one positive so the minus sign will drop out. Hooke's law for a spring states that:

$$F = -ky \qquad 14.$$

Where F is the stretching force, y is the amount of stretch (displacement) and k is the spring constant. The minus sign indicates the direction of the force the spring exerts on the object. The force is equal to mass times acceleration so $ma = -ky$ or $m/k = -y/a$. With this substituted in equation 13, the formula for the period of a mass on a spring is:

$$T = 2\pi\sqrt{\frac{m}{k}} \qquad 15.$$

## PENDULUM

Equation 13 can be rewritten to apply to a pendulum. It becomes:

$$T = 2\pi\sqrt{\frac{L}{g}} \qquad 16.$$

Where L is the length and g is the acceleration of gravity. Actually, this is a simplification and is true only if the angle of the swing is small. The length of the arc of the swing should be no more than one or two percent of the length of the pendulum.

## ENERGY

A simple harmonic motion repeats itself at regular intervals and the motion that occurs represents the continuous conversion of potential energy (gravitational or elastic) to kinetic energy and back.

The total energy is completely in the form of kinetic energy when the object passes through the equilibrium point ($\frac{1}{2}mv_{max}^2$). When equations 11 and 5 are substituted for $v_{max}$, the total energy is:

$$E_t = 2\pi^2 f^2 R^2 m \qquad 17.$$

Where m is the mass.

At the end of the swing, the total energy is in the form of potential energy. For a mass on a spring it is given by:

$$E_t = \frac{1}{2}kR^2 \qquad 18.$$

and for a pendulum by:

$$E_t = \tfrac{1}{2}mgR^2/L \qquad 19.$$

Where L is the length of the pendulum and R is the amplitude of the swing.

At points between the equilibrium point and the end of the swing the formulas are:

$$E_t = \tfrac{1}{2}ky^2 + 2\pi^2 f^2 (R^2 - y^2)m \qquad 20.$$

for the mass on a spring and for the pendulum:

$$E_t = \tfrac{1}{2}mgy^2/L + 2\pi^2 f^2 (R^2 - y^2)m \qquad 21.$$

The first term in each of these equations is the part of the energy in the form of potential energy and the second term is kinetic energy. Keep in mind that equation 21 (first term) is only an approximation ($h \approx y^2/2L$) and holds true only if the angle of the swing is small.

EXAMPLE: Find the kinetic energy, elastic potential energy and the total energy of the mass on the spring in the previous example. ($y = 4 \sin 10\pi t$) at the end of 0.01 s). Assume the mass is 200 g. The spring constant is 197 500 dynes/cm.

Given: (see previous example)

Solution:

$$E_K = 2\pi^2 (5\ \text{Hz})^2 (4^2 - 1.24^2)(200\text{g})$$

$$= 1\ 430\ 000\ \text{erg (See 2nd term of equation 20).}$$

$$E_P = \tfrac{1}{2}(197\ 500\ \text{dynes/cm})(1.24\ \text{cm})^2$$

$$= 152\ 000\ \text{erg (See 1st term of equation 20).}$$

The total energy should be the sum of these two (1 580 000 erg) or can be calculated by equation 17:

$$E_t = 2\pi^2 (5\ \text{Hz})^2 (4\ \text{cm})^2 (200\ \text{g})$$

$$= 1\ 580\ 000\ \text{erg}$$

or by equation 18:

$$E_t = \tfrac{1}{2}(197\ 500\ \text{dynes/cm})(4\ \text{cm})^2$$

$$= 1\ 580\ 000\ \text{erg} = 0.158\ \text{J}$$

PROBLEMS

Module M 12 SIMPLE HARMONIC NOTION

1. A pendulum bob is made of iron and swings with a small amplitude. A large magnet is raised up under the pendulum effectively increasing the downward acceleration. Does the period increase or decrease? Explain.

2. A magnetic coil is placed around an iron mass on a spring increasing the downward acceleration when it is switched on. Will this change the period? Explain.

3. A brass ball and a cork ball of equal diameters are used as pendulum bobs on threads of equal length. Is their periods the same? In actual practice what happens?

4. The thread supporting a pendulum bob is clamped to the support. If the clamp is loosened and the thread pulled upward, what happens to the period as the length gets shorter? Since work is done on the pendulum, does the energy of the vibration increase?

5. Explain why "cheap" pendulum clocks would run slow or fast with changes in temperature.

6. Define: SHM, amplitude, period, frequency and angular frequency.

7. At what part of the swing of a body in simple harmonic motion (end of swing or equilibrium point) is the displacement zero? Maximum? Where is the velocity zero? Maximum? Where is the acceleration zero? Maximum?

8. A quartz crystal oscillates (thickness vibration) at a series resonance frequency of 422.3 kHz. What is the period? What is the angular frequency?

9. Accelerometers are attached to an airplane radio reciever along each of the three axis. During a vibration test (along one axis), a frequency of 150 Hz is used on the 10 kg reciever. The amplitude of the SHM vibration is increased until the maximum acceleration indicates 98 $m/s^2$ (10 g's). What is the amplitude of vibration? What is the maximum velocity? What is the maximum force applied to the reciever?

10. The ends of a tuning fork vibrate approximately in simple harmonic motion. If the frequency is 256 HZ, what is the period and angular frequency. If the amplitude is 0.5 mm, what is the maximum velocity and maximum acceleration.

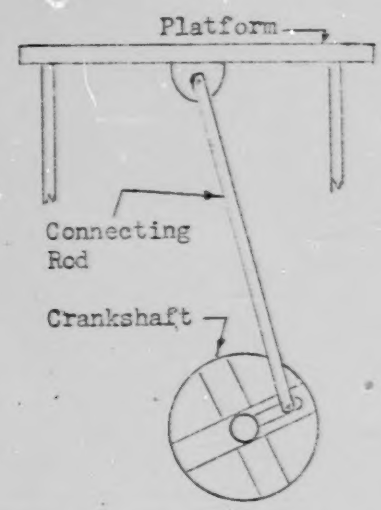
11. A swag lamp hangs 1.2 m (center of gravity) from the ceiling. If it were set to swinging, what would be the period. Assume it acts as a simple pendulum.

12. A large transformer is being set in place by a crane. If the length of the cable supporting it is 3 m long (from the point of support to the center of gravity), find the period with which it would swing. Assume it acts as a simple pendulum. What is the frequency?

13. The amplitude of the swinging transformer in the previous problem is 10 cm and it has a mass of 1200 kg. How much energy is stored in the form of vibration energy. Hint: calculate either the maximum kinetic energy or the maximum potential energy.

14. What is the maximum velocity of the swinging transformer in the previous problem? What is the maximum acceleration? What force would be required to hold it at the end of the swing?

INFORMATION: One form of a vibration tester is shown in the diagram. If the motor - driven crankshaft has a small radius compared to the length of the connecting rod, the platform will vibrate in approximately SHM. Objects being tested are clamped to the platform. Amplitude and frequency are adjustable. Modern vibration testers are driven by an electromagnetic shaking device similar to a dynamic loudspeaker. Large equipment is tested using a hydraulicly driven device. The platform is usually driven from side to side rather than vertically.



15. If the vibration tester described in the diagram above has an amplitude of 0.003 in, what is the frequency if the maximum acceleration is 320 $ft/s^2$ (10 g's)?

16. If a loose object was sitting on the platform of the previous problem, at what frequency would the object lose contact with the platform? The amplitude is 0.003 in.

17. A 0.5 kg mass on a spring with a spring constant of 16 N/m will vibrate with what period?

18. A spring stretches 15 cm when a load of 0.25 N is applied. If a 100 g mass is attatched to it (after the load is removed). What will be the period of vibration? If the amplitude is 5 cm what will be the total energy stored in the spring?

19. Write the displacement equation for the vibration tester in prolem 15. The frequency is 180 Hz and the amplitude is 0.003 in. Time begins as the platform moves upward through the equilibrium position.

20. What is the displacement of the platform in the previous problem 1 ms after passing upward through the equilibrium position?

21. If $y = 1.2 \sin 1000\pi t$ (distances in millimeters, time in seconds) is the equation for the SHM displacement of a point on a loudspeaker driven by a pure tone, find the amplitude, total range of the motion, angular frequency, frequency, period, maximum velocity, and maximum acceleration of the point.

22. What is a damped vibration? Describe viscous, magnetic and elastic damping. Name one practical example of each type.

ANSWER KEY (PROBLEMS)

## Module M 12 SIMPLE HARMONIC MOTION

1. Decreases. g is in the denominator of formula for T.
2. No. Mass is pulled downward, vibration is the same at a lower position.
3. Yes, T does not depend on mass for a pendulum. Friction has a greater effect on the light cork ball so it lags slightly behind.
4. Decreases since L decreases. Yes.
5. Length of pendulum increases. More expensive clocks compensate for temperature effects.
6. See Information Sheet
7. Eq. pt., end; end, eq. pt.; eq.pt., end.
8. 2.37 μs, $2.65 \times 10^6$ rad/s
9. 0.11 mm, 0.1 m/s, 980 N
10. 3.91 ms, 1610 rad/s, 8.04 m/s, 12 900 $m/s^2$.
11. 2.2 s
12. 3.48 s, 0.288 Hz
13. 19.6 J
14. 0.181 m/s, 0.327 $m/s^2$, 393 N
15. 180 Hz
16. 56.9 Hz (It "floats" part of the time when the platform moves downward at an acceleration of 32 $ft/s^2$).
17. 1.11 s
18. 1.54 s, 8330 erg
19. $y = 0.003 \sin 360\pi t$
20. 0.00277 cm
21. 1.2 mm, 2.4 mm, $1000\pi$ rad/s, 500 Hz, 0.002 s, 3.77 m/s, 11 800 $m/s^2$
22. A vibration in which the amplitude decreases as a function of time. Shock absorbers on a car, short circuit of a swinging coil, damper on phonagraph pick-up.

EXPERIMENTS

## Module M 12 SIMPLE HARMONIC MOTION

PURPOSE: The purpose of these experiments is to study simple harmonic motion by measuring the period of a mass oscillating on a spring and of a pendulum. Formulas for both objects are derived from equations of SHM. The acceleration of gravity is measured with considerable accuracy with the pendulum.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

INFORMATION: Hooke's law for a spring states that:

$$F = k\Delta y$$

Where F is the stretching force and $\Delta y$ is the change in length of the spring. The letter k is called the spring constant and depends on the stiffness of the spring. It can be calculated with the equation stated above when F and $\Delta y$ are known. Your first step in experiment A is to determine the spring constant.

The period of a mass vibrating on a spring is given by the equation:

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Where m is the mass on the spring plus about 1/3 the mass of the spring and k is the spring constant. If the mass on the spring is large, the mass of the spring can be ignored. This formula is derived from equations of simple harmonic motion.

The period of a simple pendulum is given by the formula:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Where L is its length and g is the acceleration of gravity. This is a simplified version which is accurate only if L is large compared to the arc of the swing. The longer you can make the pendulum and the shorter arc you allow it to swing, the more accurate your results will be.

## EXPERIMENT A MASS ON A SPRING

EQUIPMENT:

1. Hooke's law apparatus (Sargent-Welch #0569)
2. Weights
3. Spring
4. Unknown weight supplied with a hook.
5. Timer
6. Balance scale

Check to see if all the equipment is available before you start. Ask the instructor if there are any questions.

PROCEDURE:

1. Attach the spring to the weight hanger (with pointer) and support it from the spring holder. The pointer should be set in front of and parallel to the face of the mirror scale.

2. Place a 50-gram mass on the hanger. This is done primarily to take up slack in the spring.

3. Adjust the mirror scale by sliding it up or down the support rod so the upper part of the scale is adjacent to the pointer.

4. Read the position of the pointer by lining it up with its image in the mirror scale. Record the position on the data sheet. Read the positions as accurately as possible.

5. Place 200 g on the hangar. Read and record the new position.

6. Calculate the increase in length ($\Delta y$) of the spring and calculate the weight (stretching force) of the 200 g mass in dynes.

7. Calculate the spring constant by using Hooke's law using the results of step 6.

8. Measure the mass of the unknown weight in grams.

9. Calculate the period of the mass when it vibrates suspended from the same spring using the results of steps 7 and 8.

10. Remove the hanger from the spring and replace it with the unknown weight.

CAUTION: It is not necessary to give the mass a large amplitude. The period will be the same for an amplitude of 1 cm as with one of 10 cm. Do not stretch the spring more than a few centimeters. A permanent set will result.

11. Measure the time required for 25 or 30 vibrations of the mass with the timer.
    NOTE: Start the timer at the bottom of the swing. Count zero when the timer is started.

12. Calculate the period using the results of step 11.

13. Compare the results of steps 9 and 12 by calculating the percentage difference.

14. Using the results of step 12, calculate the frequency the angular frequency, maximum velocity, maximum acceleration and total energy of the motion.

15. Write an equation of the motion assuming the time begins as the mass passes through the equilibrium position on its way upward. Assume the amplitude is 2 cm. = R

16. Return the apparatus to the proper drawer.

## EXPERIMENT B THE PENDULUM

EQUIPMENT:

1. Metal ball on a light string or thread
2. Suspension apparatus
3. Support rod (1.25 m) and table clamp
4. Timer
5. Meter sticks or metric tape

Check to see if all the equipment is available before you start. Ask the instructor if you have any questions.

PROCEDURE:

1. Attach the table clamp with support rod to the edge of a lab bench or a sturdy table.

2. Attach the suspension apparatus to the top of the support rod so it extends over the edge of the bench.

3. Clamp the pendulum thread to the suspension apparatus so the thread will oscillate from the bottom edge. USE THE CLAMP. The thread should be clamped so the ball is about 1 cm above the floor.

4. Start the pendulum with an amplitude of no more than 3 cm. It should move straight back and forth and not around in a circular or elliptical path.

5. Measure the time for about thirty complete oscillations. (Count zero when the timer is started. Count one after one complete oscillation, etc.). Record both the number of oscillations and the time.

6. Calculate the period from the results of step 5.

7. Measure the length of the pendulum to the center of the ball as accurately as you can.

8. Calculate the acceleration of gravity from the results of steps 6 and 7 using the formula for the period of a pendulum.

9. The acceleration of gravity has a value of 980.24 in eastern Nebraska. Using this as the standard value calculate the percentage error in your calculations.

10. Return the apparatus to the proper drawer.

## EXPERIMENT C THE INERTIAL BALANCE

This experiment was a part of "The Laws of Motion" (Module M 7). It is repeated here since it involves vibratory motion. The performance of this experiment is optional.

INFORMATION: Inertia is the property of matter that causes (1) a body at rest to remain at rest, or (2) a body in motion to remain in motion at constant velocity unless acted upon by an externally applied force. Newton's first law states that all matter has inertia. When you measure the mass of an object, you are measuring its inertia. A body of large mass has a large amount of inertia; a body of smaller mass has less inertia.

Weight is the pull of gravity on an object and is proportional to its mass. An object with a large mass will weigh a large amount; a small mass will weigh less.

EQUIPMENT:

1. Inertial balance (Sargent-Welch Cat.#0875)
2. Six 100 g slotted masses
3. One 3 in. C-clamp
4. One stop clock
5. Harvard trip balance
6. Various support rods and clamps

Check to see that all equipment listed is available. Obtain a data sheet from the instructor.

PROCEDURE

1. Securely clamp the inertial balance to a laboratory bench using the C-clamp. See figure 5.

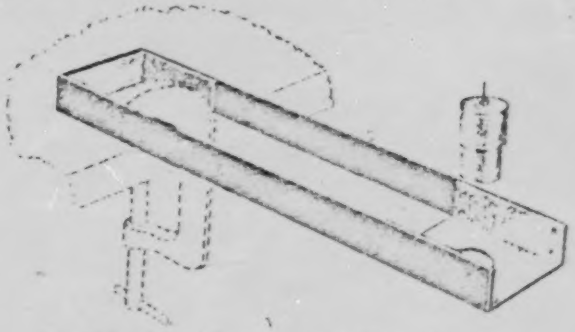


Figure 5. The Inertial Balance
By permission: The Sargent-Welch Scientific Co.

2. Plug the stop clock into a wall socket. Test the remote operating switch. NOTE: The clock is decimalized; each revolution of the large hand is ten seconds.

3. Place a 100 g mass in the center of the balance pan.

4. Deflect the balance pan about 3/8 to ½ in to one side by finger pressure. Release the balance so it oscillates freely.

5. After several oscillations, (when the mass stops moving on the pan) measure the time for fifty complete cycles.

   NOTE: Start the clock at one end of the swing; count "zero" at the same instant you start the clock.

   NOTE: Be sure to count complete cycles. One complete cycle is a swing over then back to the starting point.

6. Record the time for fifty cycles on the data sheet.

7. Repeat steps 4, 5 and 6, with 200 g, 300 g, 400 g, 500 g, and 600 g on the balance pan.

8. Calculate the frequency, period and square of the period for each trial and record on the data sheet.

9. On the graph paper provided, plot the mass horizontally and the period and the square of the period vertically. Which curve shows a linear relationship? Which variable is mass proportional to?

10. Remove the slotted masses from the pan and place the unknown mass through the hole in the balance pan. It should rest on the collar formed by the larger diameter.

11. Repeat steps 4, 5, and 6 with the unknown mass.

12. Determine the mass of the unknown by plotting the square of the period on the graph.

13. Assemble the stand, rod, clamp, and string as shown in figure 6. Suspend the unknown mass so the collar is not resting on the balance pan.

14. Repeat step 4, 5 and 6 with the unknown mass suspended.

15. Determine the mass as in step 12 and compare. Does the pull of gravity have a significant effect on the mass of the unknown?

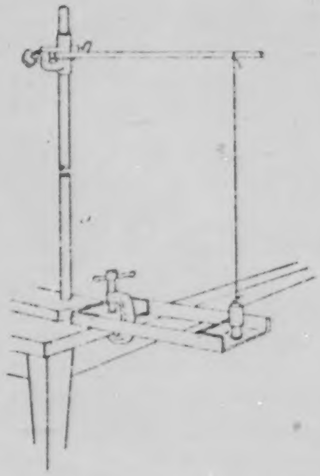


Figure 6. The Unknown Mass
By permission: The Sargent-Welch Scientific Company

16. Measure the mass of the unknown using the Harvard trip balance.

17. Calculate the percentage difference in the graph value of the unknown mass and that measured on the Havard trip balance.

18. Dismantle the equipment and put it away.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: P 1

Title: Mechanical Properties of Matter

Module Contents:
1. Density
2. Elasticity
3. Stress and strain
4. Mallibility and ductility

Program: This module has been prepared especially for students in:

1. Welding Technology
2. Machine Tool and Design Technology
3. Industrial Plastics Technology
4. Manufacturing Engineering Technology

Purpose: The purpose of this module is for you to learn how solid materials behave when subjected to forces and torque. It covers elasticity and strength of materials. These subjects are important for any student involved in manufacturing processes.

Producer: Gene Waring

Date Produced: December 1976

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## MODULE P 1 MECHANICAL PROPERTIES OF MATTER

### OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define mass and weight density.
2. Define tension, compression and shear.
3. Define elasticity, stress, strain, elastic limit, ultimate strength and factor of safety.
4. State the relationship between stress and strain (Hooke's law) for stretching, volume and shearing deformations.
5. State the difference between elastic and plastic deformations.
6. Solve various applied problems involving the definitions and laws in objectives one through four.
7. Define hardness, ductility and malleability.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

### SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of elasticity. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 6) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read all of Chapter 10, pages 239-259.

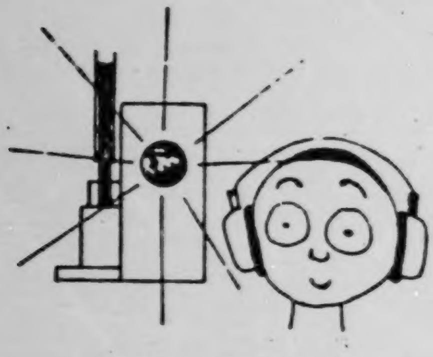
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read Chapter 10 Section 10.1 pages 121-122 and Sections 10.8-10.12 pages 127-131. Also read Chapter 12, section 12.8, pages 157-159.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read Chapter 14, section 14.3, pages 184-187 and section 14.6, pages 189-194. Also read the Information Sheet (A).

E. Physics for Technology, Betts, J., Reston Publishing Co., Inc., 1st ed., 1976. Real all of chapter 5, pages 57-74.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read all of chapter 13, pages 196-209.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Bubble Model of A Crystal: Structure and Boundries (BFA-Ealing 84-0116)
B. Bubble Model of A Crystal: Deformation and Dislocations (BFA-Ealing 84-0124)
C. Identifying Solids by Density (BFA-Ealing 80-3262)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving elasticity and density problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. A "Hooke's law" experiment with a spring was a part of Module M 8 (Work and Energy). If you did not perform that experiment or if you want to repeat it, obtain a data sheet and the equipment from your instructor. The instructions are repeated in this module (yellow paper).

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

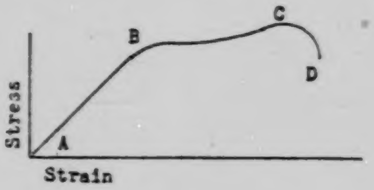
Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

## Module P 1 MECHANICAL PROPERTIES OF MATTER

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The figure represents the stress-strain curve for a certain metal. Hooke's law is obeyed only in the section between A and B.



T - F 2. The weight density of a substance is less at sea level than it is on top of a mountain.

T - F 3. Shearing stresses tend to change the shape of an object.

T - F 4. If the elastic limit stress is not exceeded then stress is proportional to strain.

T - F 5. A ductile substance is one that is capable of being hammered or rolled into thin sheets.

6. If an object has a mass of 29 g and a volume of 5 $cm^3$, its density in kilograms per cubic meter is:

a) 5.80 c) 145

b) 172 d) 5800

7. When a stress of 19 000 $lb/in^2$ is applied to an aluminum cable, what is the strain? ($Y = 10 \times 10^6$ $lb/in^2$)

a) 0.0019 c) $1.9 \times 10^{11}$

b) 526 d) 1900

8. A force of what magnitude (in pounds) will cause a stress of 5000 $lb/in^2$ in a 1 in diameter rod?

a) 5000 c) 6370

b) 3930 d) 9840

9. A power punch makes a 2 inch hole in sheet aluminum which is 0.01 in thick. What force is required if the ultimate strength is 21 000 $lb/in^2$?

10. A 14 ft concrete column is 1 ft in diameter. It carries a load of 90 000 lb. How much will its length decrease? ($Y = 3\ 200\ 000$ $lb/in^2$)

## ANSWER KEY TO THE SELF-EVALUATION TEST

## Module P 1 MECHANICAL PROPERTIES OF MATTER

| Question-Answer | If you missed this question, you are directed to these learning activities. |
|---|---|
| 1. T | I Reading |
| 2. F | I Reading |
| 3. T | I Reading |
| 4. T | I Reading or II Listening/Viewing |
| 5. F | I Reading |
| 6. d | III Solving Problems and I Reading |
| 7. a | III Solving Problems and I Reading |
| 8. b | III Solving Problems and I Reading |
| 9. 1320 lb | III Solving Problems and I Reading |
| 10. 0.04 in | III Solving Problems and I Reading |

## INFORMATION SHEET

## Module P 1 MECHANICAL PROPERTIES OF MATTER

Whenever a force is applied to an object, a reaction is set up between the molecules that make up the object. The molecules near the point of application are pushed closer together than normal. There is a deformation at the point of application which spreads throughout almost all of the object. The molecules at C in figure 1, which have been pushed downward by the force, push other molecules downward and outward. The push of molecule against molecule is just the right amount to create the equal and opposite reaction force on the object exerting the force.

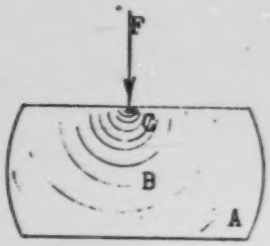


Fig 1

If the object was made of styrofoam, the indention at point C would be apparent. In fact, with larger forces, the indention would probably be permanent. If the object was a plank, the bending would also be apparent but it would recover its original shape when the force is removed. A steel object, however, would have a slight indention which would hardly be noticeable. Still, the forces displace molecules some distance away, even in steel.

Instead of compressing the molecules, forces can be applied in such a way that the molecules are pulled further apart (stretching or tension). Forces can also be applied so that molecules tend to slide past each other (shearing). Although there may be different kinds of stress and strain, they are related the same way. It's simply a matter of defining the two quantities correctly.

### STRESS

There are three kinds of stress: tensile or compressive, shear and bulk. Whenever an object tends to lengthen or shorten a tensile or compressive stress is applied. The stretching of a cable or the shortening of a support column are examples. If an object tends to be cut in two, a shearing stress is applied. An example would be a rivet or bolt being sliced in two by side ways forces. Bulk stresses tend to decrease the volume of the object. An object submerged in liquid has forces on the top, sides and bottom, for example.

Stress is the internal reaction to the applied force and is defined as:

$$\text{stress} = \frac{F}{A} \qquad 1.$$

Where F is the applied force and A is the area over which the force is distributed. The area used in equation 1 depends on the kind of stress being applied. A general rule is:

Use one-half the new area that would be formed if enough stress is applied to break or cut the object in two. For bulk stress simply use the total external surface area of the object.

Notice that the word pressure is the common name for bulk stress.

**Example:** A single 1.5 in cable supports the weight of a 6000 lb bucket of cement when being moved to the dumping site by a crane. Find the stress in the cable.

**Given:** $F = 6000$ lb
$d = 1.5$ in

**Solution:**

$$\text{Stress} = \frac{F}{A} = \frac{6000\ \text{lb}}{\pi(0.75\ \text{in})^2} = 3400\ \text{lb/in}^2$$

**Note:** If enough force was applied to the cable to break it, the newly formed surface area is the cross-section of the cable.

**Example:** If the center plate (figure 2) pulls on the 0.5 in rivet with a force of 500 lb, find the shearing stress in the rivet. Note that if enough force was applied the rivet would be cut in two places:

Given: $F = 500$ lb
$d = 0.5$ in

Solution:

$$\text{Stress} = \frac{500\ \text{lb}}{2\pi(0.25\ \text{in})^2} = 1270\ \text{lb/in}^2$$

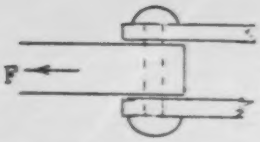


**Fig 2**

**Example:** Find the bulk stress on a 2 ft cube if the average force on each face is 28 800 lb.

**Given:** $F = 28\ 800$ lb on each of six faces.
$A = 3456\ \text{in}^2$ (all six faces).

**Solution:**

$$\text{Stress} = \frac{(6)28\ 800\ \text{lb}}{3456\ \text{in}^2} = 50\ \text{lb/in}^2$$

## STRAIN

Stress is the cause. Strain is the effect. Although the two words are used interchangeably or together in ordinary conversation, they are not the same thing. Death of a loved one is a stress. Sadness is the strain or result of the stress. A speaker applies a stress to a crowd of people by something he says. Anger is the strain. A lion applies a stress to a herd of antelope (by its presence). Fear is the strain.

A force applies a stress to an object. The strain is the fractional change in length, shape or volume depending on whether the stress is tensile or compressive, shear or bulk. Strain is defined by the following formulas:

$$\text{Tensile strain} = \frac{\Delta L}{L} \qquad 2.$$

Where $\Delta L$ is the change is length and L is the original length.

$$\text{Shearing strain} = \frac{x}{h} \qquad 3.$$

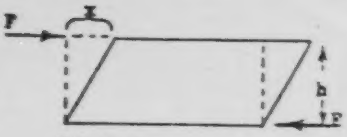


Fig 3 Shear

Where x is the sideways movement caused by the shearing force (see figure 3) and h is the vertical height.

$$\text{Bulk strain} = \frac{\Delta V}{V} \qquad 4.$$

Where $\Delta V$ is the change in volume and V is the original volume.

Example: A 100 ft cable increases in length by 4 in when a load is lifted by the cable. Find the tensile strain.

Given: $\Delta L = 4$ in

$L = 1200$ in

Solution: $\text{strain} = \frac{\Delta L}{L} = \frac{4 \text{ in}}{1200 \text{ in}} = 0.00333$

Notice that strain is a dimensionless quantity.

## MODULUS OF ELASTICITY

Elasticity of a substance is the ability of a material to regain its original shape after a stress is removed. A material is said to be very elastic if it rebounds to its original shape quickly and with large force. It is not dependent on how far it stretches. A rubber band stretches a long ways but the forces involved are quite small so rubber is not very elastic. To stretch a steel wire even a small amount requires very large forces. Steel, then is very elastic.

Hooke's law states that strain is proportional to stress for a given material if the stress is not too great:

$$\text{stress} = M \text{ strain} \qquad 5.$$

Where M is the modulus of elasticity of the substance. The modulus of elasticity is a property of matter. Different materials can be identified by determining the modulus of elasticity.

For a given substance the modulus of elasticity depends on the kind of stress applied. The tensile modulus (Y), shear modulus (S) and bulk modulus (B) are not the same for a given substance. See table 1.

**Table 1 Elastic Constants**

| Substance | Y lb/in$^2$ | S lb/in$^2$ | B lb/in$^2$ | TEL lb/in$^2$ | UTS lb/in$^2$ |
|---|---|---|---|---|---|
| **Aluminum** | $10 \times 10^6$ | $3.4 \times 10^6$ | $11 \times 10^6$ | $19 \times 10^3$ | $21 \times 10^3$ |
| **Brass** | $13 \times 10^6$ | $5.1 \times 10^6$ | $8.5 \times 10^6$ | $55 \times 10^3$ | $67 \times 10^3$ |
| **Lead** | $2.3 \times 10^6$ | $0.8 \times 10^6$ | $1.1 \times 10^6$ | | |
| **Steel** | $29 \times 10^6$ | $11.7 \times 10^6$ | $23 \times 10^6$ | $40 \times 10^3$ | $80 \times 10^3$ |
| **Tungsten** | $51 \times 10^6$ | $21.5 \times 10^6$ | | | $600 \times 10^3$ |
| **Rubber** | 20 | | | | |
| **Water** | | | $0.31 \times 10^6$ | | |

If the formulas for stress and strain are substituted in equation 5 and solved for the modulus of elasticity the following formulas are obtained:

Tensile modulus of elasticity (Young's modulus):

$$Y = \frac{FL}{A\Delta L} \qquad 6.$$

Shear modulus of elasticity:

$$S = \frac{Fh}{Ax} \qquad 7.$$

Bulk modulus of elasticity:

$$B = \frac{PV}{\Delta V} \qquad 8.$$

In equation 8 the stress (F/A) is replaced with the symbol for pressure (P).

ELASTIC LIMIT AND ULTIMATE STRENGTH

Hooke's law (equations 5,6,7 and 8) is valid only if the material returns to its original shape after the deforming stress is removed. Figure 4 shows the relationship between stress and strain for two different materials under tensile stress. The graphs are straight lines as long as the elastic limit stress is not exceeded. The elastic limit stress (EL) is usually called, simply: The elastic limit. If a stress greater than the elastic limit stress is applied, the object is deformed to a point where it will no longer return to its original shape. Beyond this point, the deformation is said to be plastic.

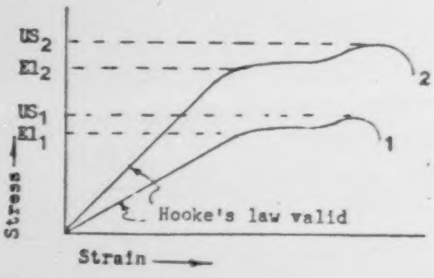


Fig 4 Elasticity

If the stress is increased after reaching the elastic limit, the strain (deformation) increases faster than before. If a stress is applied equal to the highest point on the graph, the object will break. This maximum value of the stress is called the ultimate stress or ultimate strength of the material.

The values of the elastic limit stress and ultimate strength for a given material are different for tensile, shear and bulk stresses. Table 1 includes the tensile elastic limit stress and the ultimate tensile strength for some materials.

## FACTOR OF SAFETY

In the design of any structure, the engineer must determine what load the structure is expected to carry. The expected load determines the stress to be expected or working stress. The engineer must design the structure so the working stress is considerably less than the ultimate strength. The ratio of ultimate strength to working stress is called the factor of safety:

$$\text{Factor of safety} = \frac{\text{Ultimate strength}}{\text{Working stress}} \tag{9}$$

The factor of safety used is different for different materials, since the ultimate strength may be only slightly larger than the elastic limit for some materials and considerably larger for others. Compare aluminum and steel, for example, in Table 1. The actual stress must not approach the elastic limit, so the working stress must be less also. For aluminum the factor of safety may be as low as 2.5 while for steel it may have to be 3.5 or more.

## MALLEABILITY, DUCTILITY AND HARDNESS

If a rod or wire can be drawn through a hole slightly smaller than its own diameter, it is said to be ductile. In general, the smaller the diameter of the wire to which it can be drawn the higher degree of ductility.

Malleability is that property of materials that make them capable of being hammered or rolled into thin sheets. Gold can be rolled into sheets so thin that a stack of 300 000 sheets would only be an inch high. Gold is, therefore, very malleable.

A material that will scratch another material at low speed is harder than the material that was scratched. A relative hardness scale (Moh's) is given in Table 2. These are minerals and the scale is usually used to identify other materials by a scratch test. This scale is not meant to indicate that diamond (10) is five times harder than gypsum (2) or that feldspar (6) is twice as hard as calcite (3). If an unknown material will scratch quartz (7) but topaz (8) will scratch it, then the material has a hardness somewhere between that of quartz and topaz.

1. Talc
2. Gypsum
3. Calcite
4. Fluorite
5. Apatite
6. Feldspar
7. Quartz
8. Topaz
9. Corundum
10. Diamond

Table 2
(Moh's Hardness Scale)

## DENSITY

The density of a material is well defined in your textbooks so no further discussion is necessary here.

## PROBLEMS

## Module P 1 MECHANICAL PROPERTIES OF MATTER

1. Distinguish between stress and strain.

2. Distinguish between ductility and malleability. Is brittleness related to either of these quantities?

3. Distinguish between elastic limit and ultimate strength. Are the yield point and breaking point related to either of of these quantities?

4. Distinguish between mass density and weight density. If one is known, how would you find the other?

5. Distinguish between elastic and plastic deformations. To which of these does Hooke's law apply?

6. An aluminum frame is, effectively, 2.5 ft long, 1 ft wide and 0.05 in thick. How much more would this frame weigh if it had been made of steel? Densities of aluminum and steel are 168.5 $lb/ft^3$ and 489 $lb/ft^3$, respectively.

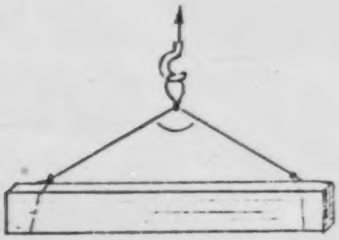
7. Steel bar stock 3 x 3 in comes in lengths of 12 ft. How much does one bar weigh if the weight density is 489 $lb/ft^3$?

8. Steel round stock 7.65 cm in diameter is purchased in lengths 3.66 m long. What is the mass of one length in kilograms if the density is 7.83 $g/cm^3$?

9. Plastic pipe has an outside diameter of 5.1 cm and as inside diameter of 4.4 cm. What is the mass of a 4 m length if the density is 1.41 $g/cm^3$? Give your answer in kilograms.

10. A 0.5 in steel bolt is tightened with a nut. As the nut is tightened, it exerts tensile forces of 0.5 ton, 1 ton, 1.5 ton, 2 ton and 2.5 ton on the bolt. Find the stress in each case. What force must the nut exert to apply a stress equal to the elastic limit (40 000 $lb/in^2$) ? What force must the nut exert to break the bolt? The ultimate tensile strength is 80 000 $lb/in^2$.

11. If the steel bolt in problem 10 has a Young's modulus of 30 000 000 $lb/in^2$, find the strain at each step as the bolt is tightened. The stresses in pounds per square inch are 5090, 10 200, 15 300, 20 400 and 25 500. If the bolt was originally 5 in long, what is the increase in length at each step?

12. 

Twenty lengths of the bar stock described in problem 7 weigh 7340 lb. They are being lifted by a crane with the use of a sling as shown. Each end of the sling is a steel cable that makes a 45° angle with the vertical. What is the tension in each cable? Note: the forces are concurrent at the hook. What is the stress in the cables if they have an effective diameter of 0.42 in. The elastic limit stress is 40 000 lb/in$^2$ and the ultimate strength is 80 000 lb/in$^2$. Is this arrangement safe considering that there will be some jerking of the load as it is lifted? What is the factor of safety?

13. A punch press is used to make steel washers with an outside diameter of 2.223 cm and an inside diameter of 0.953 cm. The washers are made one at a time. How much area is cut if they are 0.0762 cm thick? If the ultimate shearing strength of the metal is 4.14 x 10$^8$ N/m$^2$, what force is required in newtons to make the washer? How many pounds is this ? How many tons?

14. What force is required in newtons, pounds and tons to make the washer of problem 13 if it was made of aluminum whose ultimate shearing strength is 1.38 x 10$^8$ N/m$^2$?

15. What force is required in newtons, pounds and tons to make the washer of problem 13 if it was made of brass whose ultimate shearing strength is 2.41 x 10$^8$ N/m$^2$?

16. If the punch press used to make the steel washers in problem 13 can exert a maximum force of 18 ton, what is the maximum thickness the washers could have? The inside diameter is 0.953 cm and the outside diameter is 2.223 cm. The ultimate shearing strength is 4.14 x 10$^8$ N/m$^2$.

17. A tension test speciman is made of a 5 in piece of 3/4 in round stock. A 2 in section in the center is turned to 1/2 in diameter and the ends are threaded. In the testing machine, the 2 in section increases in length by 0.0030 in under a load of 9000 lb without reaching the elastic limit. What is the stress and strain at this point. Calculate Young's modulus for this material.

ANSWER JET (PROBLEMS)

Module P 1 MECHANICAL PROPERTIES OF MATTER

1. Stress is force per unit area, strain is the fractional change.

2. See text. If a material fails after a large deformation it is ductile. If it fails with very little deformation it is brittle.

3. See text. The yield point is slightly past the elastic limit where a material continues to deform without additional stress.

4. See text. $D = dg$

5. See text. Elastic

6. 3.33lb

7. 367 lb

8. 132 kg

9. 2199 kg

10. 5090, 10 000, 15 300, 20 400, 25 500, (lb/in$^2$), 7850 lb, 15 700 lb

11. $1.7 \times 10^{-4}$, $3.4 \times 10^{-4}$, $5.1 \times 10^{-4}$, $6.8 \times 10^{-4}$, $8.5 \times 10^{-4}$
$8.5 \times 10^{-4}$in, $1.7 \times 10^{-3}$in, $2.6 \times 10^{-3}$in, $3.4 \times 10^{-3}$in, $4.3 \times 10^{-3}$in

12. $T = W/(2 \cos \theta)$ = 5190 lb, 37 500 lb/in$^2$, too close to elasic limit, 2.1.

13. 0.76 cm$^2$, 31 500 N, 7070 lb, 3.54 ton

14. 10 500 N, 2360 lb, 1.18 ton

15. 18 300 N, 4120 lb, 2.06 ton

16. 0.39 cm

17. 45 800 lb/in$^2$, 0.0015, 30 600 000 lb/in$^2$

EXPERIMENTS

Module P 1 MECHANICAL PROPERTIES OF MATTER

**PURPOSE:** The purpose of this experiment is to study Hooke's law as it applies to springs and to study the work done on and the energy stored in a spring when it is stretched or compressed.

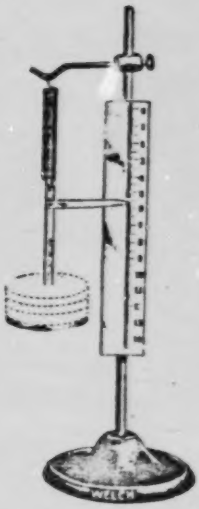
**CAUTIONS:**

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using.
3. Observe all cautions listed in the prodedure section of these instructions.

**EQUIPMENT:** Check to see if all the following equipment is available before you start.

1. Welch #569 Hooke's Law Apparatus
    - A. Stand with mirror scale
    - B. Weight hanger with pointer
2. Two spiral springs (one large, one small)
3. One set of slotted weights

**PROCEDURE:**



By permission: Sargent-Welsh Scientific Co., Instructions for Hooke's Law Apparatus

1. Set up the apparatus as shown in the diagram, supporting the large spiral spring vertically. The pointer should now be horizontal in front of the scale.

NOTE: The pointer is a part of the weight hanger. The scale has a mirror finish so you can eliminate parallax errors by reading the scale when the pointer is exactly in front of its image.

NOTE: To eliminate friction, add sufficient weights to the hanger so that the coils of the spring are slightly separated.

NOTE: Before starting your observations, be sure the pointer is near the top of the scale. Adjust by moving the spring hanger or the scale up or down on the stand. The pointer does not need to be set on zero.

2. Record the position of the pointer on the first line on the data sheet table. Read the position as accurately as you can.

3. Add a 50 g mass to the hanger and weight already in place. Read and record the new position.

4. Continue adding masses (50 g at a time) until a total of 300 g have been added. Read and record the position at each step.

5. Remove the masses in equal 50 g steps and record the position at each step.

   CAUTION: Do not add more than 350 grams to the spring. The spring will exceed the elastic limit of the metal and will not return to its original shape. The spring constant would be altered and the spring ruined.

6. Convert the masses to weight (stretching force) in dynes. Record in the table.

7. Plot a graph of the data (Force vs. displacement).

8. Does the result of the experiment thus far indicate that Hooke's law is correct? Answer this question on the data sheet.

9. Calculate the difference in successive readings of the position of the pointer. Record in the table. This gives the deflection of the spring for each 50 g step.

10. Calculate the average deflection of the spring.

11. Use the average deflection of the spring to calculate the spring constant in dynes/cm. See Information Sheets (green, pages) for discussion of springs.

# APm Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: P 2

Title: FLUIDS I (STATICS)

Module Contents:
1. Pressure and vacuum
2. Bouyancy and specific gravity
3. Pascal's principle
4. The atmosphere

Probram: This module has been prepared especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to study the principles of hydraulics. Hydraulic principles are used in various lubrication. cooling, clamping, reciprocal motion and other power and control equipment in the manufacturing industries. An understanding of hydraulic principles is essential. This module also serves as an introduction to courses in fluid power.

Producer: Gene Waring

Date Produced: January 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## Module P 2 FLUIDS I (STATICS)

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define pressure and specific gravity.
2. State the formula for pressure in a liquid and define pressure head.
3. List the value of standard atmospheric pressure in various units and in various pressure head units.
4. Describe how both mercury and aneroid barometers work.
5. State the difference between absolute and gauge pressure scales and convert from one to another in various units.
6. Describe the manometer and the Bourdon gauge.
7. Use the manometer to measure head and convert to regular pressure units (British or metric).
8. State Archimedes' principle as it applies to both floating or submerged objects.
9. List the density of water in various British and metric units.
10. Determine the specific gravity of solid objects by weighing them both in air and water.
11. Measure the specific gravity of liquids using a hydrometer.
12. State Pascal's law.
13. Calculate various applied problems that involve the definitions and formulas of objectives 1, 2, 8, 10 and 12.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of fluids. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 5 ) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 6 ) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 4 ).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet, Read the information sheets included in this booklet. They are printed on green paper (page ). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., Read chapter 11, sections 11.1-11.12, pages 265-282 and chapter 12, sections 12.8-12.20, pages 302-314.

C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 12, sections 12.1-12.9, pages 150-159.

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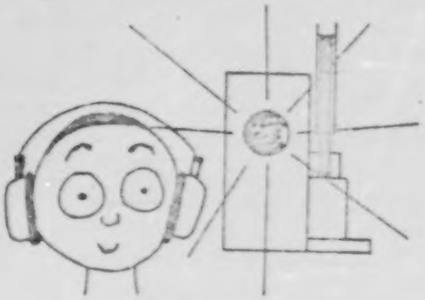
D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read all of chapter 15, pages 196-207.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 13, sections 13.1-13.6, pages 184-197 and chapter 5, section 5.1-5.2, pages 58-61.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 14, sections 14.1-14.4, pages 212-220.

II. Listening/Viewing: The following film strip with cassette tape is available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the Hitachi sound projector and must precede the viewing of the film. Ask the LRC personnel about this training.



A. Basic Hydraulics (International Harvester B1-ST)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper (page ). Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving hydrostatic problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There are 2 experiments in this module. They will give you practice in learning about pressure and specific gravity.

Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (P-2) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower that 80% will require that you repeat the test. you must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

## SELF-EVALUATION TEST

## Module P 2 FLUIDS I (STATICS)

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The density of water is 62.4 $\text{lb/in}^3$.

T - F 2. An absolute pressure of 2 atmospheres is equivalent to 3 atmospheres gauge pressure.

T - F 3. A hydrometer sinks deeper in less dense liquids to displace its own weight.

T - F 4. The pressure under an object can be decreased by increasing the area the object rests on.

T - F 5. The pressure at the bottom of a container filled with liquid does not depend on the area of the liquid surface.

6. A solid object weighs 2.4 lb in air and 1.6 lb in water. Its specific gravity is:

   a) 0.67
   b) 1.5
   c) 0.33
   d) 3

7. Which of the following does not correspond to standard atmospheric pressure or pressure head?

   a) 406.8 in (water)
   b) 1 $\text{g/cm}^2$
   c) 30 in ( mercury)
   d) $1.013 \times 10^5\ \text{N/m}^2$

8. What is the pressure in pounds per square inch measured with a mercury manometer if the levels are 21.2 in and 9.3 in? The density of mercury is 0.49 $\text{lb/in}^3$.

   a) 187
   b) 57.1
   c) 5.8
   d) 0.84

9. A force of 700 N is spread over an area of 35 $\text{cm}^2$. What is the pressure in newtons per square meters?

   a) 200 000
   b) 20
   c) 2000
   d) 0.05

OVER

10. The specific gravity of alcohol is 0.8. The difference in levels in an alcohol manometer is 16.5 cm. What is the pressure in newton's per square meter?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module P 2 FLUIDS I (STATICS)

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. F | I Reading (Information Sheet) |
| 2. F | I Reading |
| 3. T | I Reading or IV Experiment |
| 4. T | I Reading or II Listening/Viewing |
| 5. T | I Reading or II Listening/Viewing |
| 6. d | III Solving Problems |
| 7. b | I Reading |
| 8. c | III Solving Problems or IV Experiment |
| 9. a | III Solving Problems |
| 10. 1290 $N/m^2$ | III Solving Problems |

GRADING

| NUMBER WRONG | GRADE |
|---|---|
| 0 | 100 |
| 1 | 90 |
| 2 | 80 |
| 3 | 70 |
| 4 | 60 |
| 5 | 50 |
| 6 | 40 |

INFORMATION SHEET

Module P 2

## FLUIDS I (STATICS)

Whenever a force is applied to an object, it is distributed over an area and a stress is set up in the object. If the force tends to compress the object, the stress is called pressure. It is defined by the formula:

$$P = \frac{F}{A} \qquad 1.$$

The pressure can be changed by changing either the force or the area.

Example: A 180 lb man stands with all his weight on one heel of one shoe. If the heel has an area of 8 $in^2$, what is the pressure on the floor under his heel?

Given: $F = 180$ lb
$A = 8$ $in^2$

Solution: $P = F/A = 180 \text{ lb}/8 \text{ in}^2 = 22.5 \text{ lb/in}^2$

Example: Suppose the man in the previous example rocks back so his weight is on the back edge of his heel, an area of 0.5 $in^2$. What is the pressure?

Given: $F = 180$ lb
$A = 0.5$ $in^2$

Solution: $P = F/A = 180 \text{ lb}/0.5 \text{ in}^2 = 360 \text{ lb/in}^2$

## PRESSURE IN LIQUIDS

The pressure in a liquid that is due to its weight only is easily determined. Figure 1 shows a cylinder partially full of liquid where h is depth. The cylinder has a cross-sectional area A. The pressure on the bottom of the cylinder due to the weight of the liquid is given by equation 1. The force is the weight of the liquid.

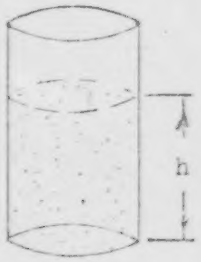


Fig 1. Pressure in liquid

Weight is given by the density formula ($W = DV$) where V is the volume. For objects of uniform cross-section throughout the entire length, the volume is given by the formula: $V = Ah$. Combining these formulas gives: $P = F/A = DV/A = DAh/A$. Since the area cancels, the formula for pressure in a liquid is:

$$P = Dh \qquad 2.$$

Where D is the weight density and h is the depth. The pressure does not depend on the area of the container. The pressure in water, for example, is the same at a given depth in the middle of a lake as it is in a quarter inch tube. The density of course must be the same in both places.

If you work a problem with mass density given instead of weight density the formula is:

$$P = dgh \qquad \text{2a.}$$

Where g is the acceleration of gravity ($9.8\ m/s^2$). Equation 2a is usually used with metric units while equation 2 is used with British.

Example: Find the water pressure at the bottom of a swimming pool at a depth of 12 ft. The density of water is $62.4\ lb/ft^3$.

Given: $D = 62.4\ lb/ft^3$
$h = 12\ ft$

Solution: $P = Dh = (62.4\ lb/ft^3)(12 ft) = 749\ lb/ft^2$
$= 5.2\ lb/in^2$

Example: Find the water pressure in newtons per square meter at a depth of 76 cm in mercury. The density is $13.6\ g/cm^3$.

Given: $d = 13.6\ g/cm^3$
$g = 980\ cm/s^2$
$h = 76\ cm$

Solution: $P = dgh = (13.6\ g/cm^3)(980\ cm/s^2)(76\ cm)$
$= 1.01 \times 10^6\ dynes/cm^2 = 1.01 \times 10^5\ N/m^2$

Pressure in a fluid always "obeys" the following rules:

1. The forces a fluid exerts on a submerged surface or wall of the container always acts in a direction perpendicular to the surface or wall.
2. At any depth in a fluid, the pressure is the same in all directions.

## PRESSURE OF THE ATMOSPHERE

The pressure of the atmosphere is due to the weight of the air. It is not as easy to calculate, however since there is no definite surface at the top and the density changes with altitude. About half the air is below the three mile altitude and 99% is lower than nineteen miles. The pressure at sea level is $14.7\ lb/in^2$ and the density is $2.2\ lb/yd^3$. Both quantities decrease to nearly zero at 20 miles altitude.

Pressure of the atmosphere is measured with a barometer. A mercury barometer consists of a tube closed at one end and filled with mercury. When the tube is inverted and the open end submerged in a container of mercury, the air pressure supports a column of mercury (Hg) in the tube about 30 inches high. The atmosphere will support a column of water in a similar way of about 34 ft. Equation 2 can be used to calculate these heights.

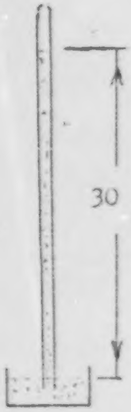


Fig 2. Mercury barometer

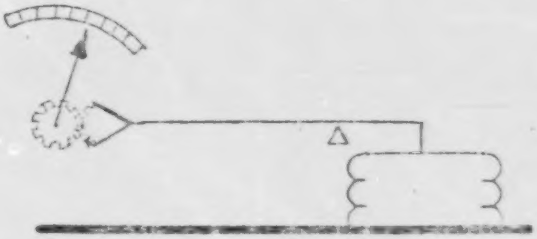


Fig 3. Aneroid barometer

The aneroid barometer consists of an evacuated can. A diaphram on one end moves as the pressure of the air on the outside changes. The movement of the diaphram is magnified by levers and transformed to movement of a pointer. The pressure is read on a dial. See figure 3.

Standard atmospheric pressure in various units are listed in Table 1. Notice that the height of a column of liquid is given in some cases. It is easier to simply state the height of a column of liquid than to use equation 2 to actually calculate the pressure. The height of the liquid and the name of the liquid make up what is known as the pressure head. The pressure head is the h in the formula P = hD.

1 atm
14.7 $lb/in^2$
30 in Hg
34 ft $H_2O$
76 cm-Hg
$10^5$ $N/m^2$

Table 1
Atmospheric Pressure

PRESSURE SCALES

If a mercury barometer was placed inside a tall bell jar, the height of the column of mercury would decrease as the air is removed. If all the air is removed there would be no column of mercury and the pressure inside the bell jar would be zero. It would contain a perfect vacuum. A barometer measures pressure on an absolute scale. There are no negative readings on an absolute scale since the zero is at the lowest possible pressure. In fact, there is no pressure at the zero reading.

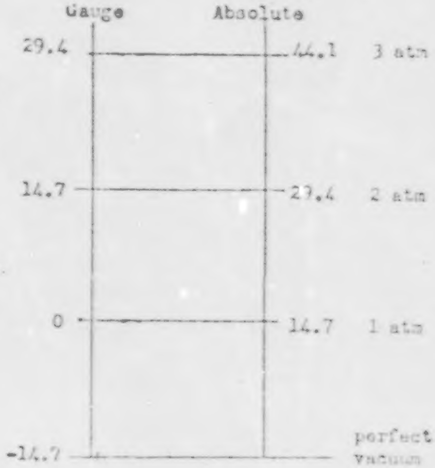


Fig 4. Pressure scales ($lb/in^2$)

Other pressure measuring devices, also, measure pressure on an absolute scale. However, some pressure gauges read the excess of pressure over that of the atmosphere. On this scale the gauge would read zero when it is open to the atmosphere. Pressures on such gauges read pressure on a gauge scale. The markings on the scales in figure 4 are in pounds per square inch. Naturally, the units could be any pressure or pressure head units. Some gauges may even mix units. They may read pounds per square inch above zero and inches of mercury below zero, for example. The markings below zero on the gauge scale are negative pressures or units of vacuum. Notice that conversion to absolute scales are accomplished by adding one atmosphere of pressure (in appropriate units) to the gauge value:

$$P_A = P_G + 1 \text{ atm} \qquad 3.$$

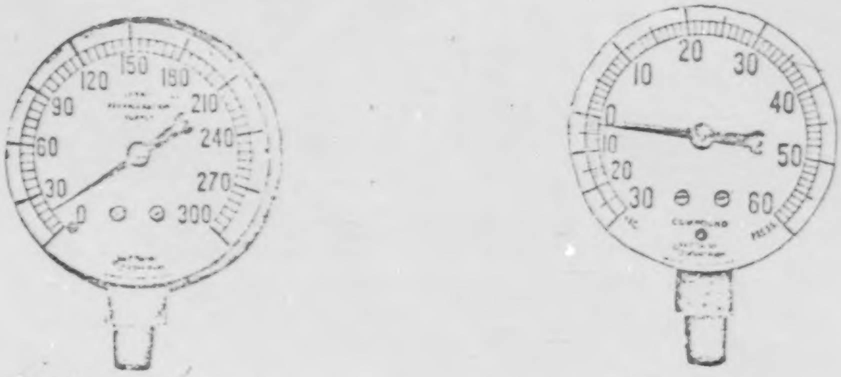


Fig 5 (a) Absolute pressure ($lb/in^2$)

(b) gauge pressure Press ($lb/in^2$) vac (in Hg)

PRESSURE MEASURING DEVICES

A simple device for measuring pressure head is the manometer. It is used for measuring relatively small gas pressures. It consists of a U-shaped tube (see figure 6) filled with liquid (usually oil, water or mercury). The pressure is applied to the tube, forcing the liquid down on that side and up on the other. The difference in levels is the pressure head. Equation 2 can be used to calculate the pressure if needed.

Manometers filled with oils or water are extremely sensitive measuring instruments. Pressure changes of 0.001 $lb/in^2$ or less are easily distinguished.

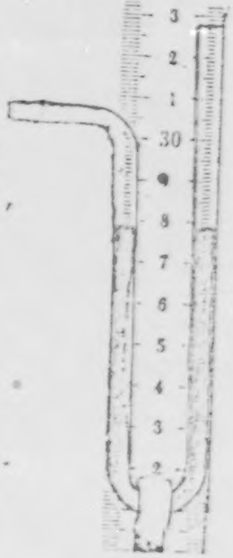


Fig 6 Manometer

Fig 7 Bourdon gauge

Bourdon gauges consist of a sealed tube that is bent into a C, helical, spiral or twisted shape. When pressure is applied, internally, the tube tends to straighten. Motion at one end of the tube is magnified by levers and transformed to rotational movement of a pointer. The pressure is read on a calibrated scale. Figure 7 shows a C-shaped Bourdon gauge.

## ARCHIMEDES' PRINCIPLE

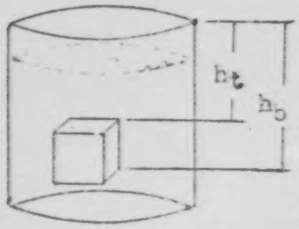


Fig 8 Submerged cube

When an object is submerged in a fluid, the upward force on the bottom due to fluid pressure is greater than the downward force on the top. This is always true because of the greater pressure at greater depths. The shape of the object makes no difference.

Figure 7 shows a submerged cube with its top and bottom horizontal. The net force on the object due to liquid pressure is the upward force on the bottom ($F_B$) minus the downward force on the top ($F_T$). The net force is called the bouyancy ($B = F_B - F_T$). Since force is pressure times area the formula becomes: $B = P_BA - P_TA$. Substituting equation 2, it becomes $B = Dh_BA - Dh_TA$ or $B = DA(h_B - h_T)$. The quantity $h_B - h_T$ is the height of the cube so $B = DAh$ The product Ah is the volume of the cube, therefore:

$$B = (D_{\text{fluid}})(V_{\text{object}}) \qquad 4.$$

Since density times volume is weight, the bouyancy must be the weight of something. The density of the fluid times the volume of the object is the weight of an equal volume of fluid or simply the weight of the fluid displaced by the object.

Equation 4 is a statement of Archimedes' principle. Note that it is not a fundamental law of nature since it is derived from various definitions and formulas. It is, perhaps, easier to understand when written in words:

> Archimedes' Principle: When an object is placed in a fluid, it is bouyed up by a force equal to the weight of the displaced fluid.

This statement applies to any shaped objects whether it is completely submerged or not. It is best to keep the following in mind, however:

> Submerged objects: An object that is completely submerged displaces its own volume of the fluid in which it is submerged.
>
> Floating objects: A floating object sinks to a point where it just displaces its own weight of the fluid in which it is floating.

Bouyant forces can be measured by finding the difference between an objects weight in air and its weight when submerged completely. The bouyant force on a floating object equals the weight of the object in air.

## SPECIFIC GRAVITY

When a person says "aluminum is lighter than steel", what does he mean? Certainly, 100 lb of aluminum is not lighter than 50 lb of steel. What is really meant by the statement is the density of aluminum is less than the density of steel. Comparisons of this kind have the unspoken intent of comparing the weight of equal volumes of different materials.

Specific gravity is a quantity that makes such a comparison:

$$\text{Sp gr} = \frac{Ds}{Dw} \qquad 5.$$

Where Ds is the density of the substance and Dw is the density of water. Notice that specific gravity has no units. The specific gravity of mercury is 13.6, for example. This means it is 13.6 times more dense than water. You should memorize the density of water in several units. See Table 2.

| |
|---|
| 62.4 lb/ft$^3$ |
| 0.036 lb/in$^3$ |
| 8.33 lb/gal |
| 1 g/cm$^3$ |
| 1000 kg/m$^3$ |
| 1 kg/ℓ |

Table 2
Density of Water

The specific gravity of a solid material can be found by weighing the object in air; then in water. The difference or loss of weight is the weight of an equal volume of water so the specific gravity is:

$$\text{Sp gr} = \frac{\text{weight in air}}{\text{loss of weight in water}} \qquad 6.$$

Hydrometers are used to measure the specific gravity of liquids. It is usually a sealed glass tube which encloses a scale and is weighted on one end. It is a floating object so it sinks until it displaces its own weight. The specitic gravity is read on the scale right at the surface of the liquid in which it floats. In "lighter" liquids it must sink deeper to displace its own weight than in "heavier" liquids.

## PASCAL'S LAW

Pascal's law was discussed in module M 9 (Simple Machines). It is repeated here for convenience.

> Pascal's law: When changes in externally applied pressures occur at one point in a confined fluid, the pressure will change by an equal amount at every other point within the fluid.

Additional information about Pascal's law is included in your textbook.

PROBLEMS

Module P 2 FLUIDS I (STATICS)

1. If one substance has a higher density than another, does this necessarily mean that the molecules of the high-density material are more densely packed? Explain.

2. Does a hydrometer that measures specific gravity of liquids that are more dense than water have the 1 at the top or bottom of the scale? Explain.

3. Distinguish between force and pressure. What are the units of each in mks, cgs and British measuring systems.

4. Describe how each of the following measuring devices work and what quantity they measure: (a) Bourdon gauge, (b) hydrometer, (c) manometer and (d) barometer.

5. When an object is submerged, does the bouyancy depend on how far below the surface the object is? When an object is floating (such as a boat) does the depth of the water make any difference?

6. If a good vacuum pump is connected to a 2 m length of glass tube with a rubber hose and the lower end of the tube is dipped in an open container of mercury, how far up the tube will the mercury rise? Explain what causes the mercury to rise in the tube. Your explanation should account for the fact that the mercury would not rise in the tube at all if the experiment is performed in a place where there is no atmosphere. What would happen if the tube ran through a rubber stopper and into a sealed container of mercury? Assume very little air space.

7. Explain what is meant by each of the following terms: (a) standard atmospheric pressure, (b) a pressure of 25 atmospheres, (c) 20 in of vacuum, (d) water head, (e) gauge pressure, (f) atmospheric pressure of 30.11 in Hg (reduced to sea level)

8. At normal atmospheric pressure, oxygen has a specific gravity of 0.00143. What is its density in $lb/yd^3$? In $kg/m^3$? What is the weight in pounds of the oxygen in a full tank if 144 $ft^3$ are compressed into it?

9. Liquid grinding coolant has a density of 10.3 lb/gal. What is its density in $kg/\ell$? What is its specific gravity? How much does a full 20 gal drum weigh in pounds?

10. A battery used for starting the engine on a portable electric welder has full charge when the electrolyte has a specific gravity of 1.250 and is discharged when it is 1.100. Find the density in each case in pounds per gallon and in kilograms per liter. Does the hydrometer float higher or lower in the electrolyte of a charged battery compared to one that is discharged?

11. Compressed air power is used in manufacturing to operate abrasive tools, drills, screwdrivers, inpact wrenches, clamping and riveting devices, air hoists and percussion tools. These usually operate at gauge pressures from 80 to 125 $lb/in^2$. Express this range in newtons per square meter. Express this pressure range on an absolute scale in atmospheres.

12. A medium sized compressed air riveting hammer operates at 100 $lb/in^2$. The piston diameter is 1.125 in. What force acts on the piston?

13. An air clamp has a cylinder bore diameter of 3 in. If the air line pressure is 90 $lb/in^2$, what is the clamping force?

14. A 100 ton roll-bed hydraulic press has a handle on the pump with a mechanical advantage of 18. If a 60 lb force is applied to this handle, what force is exerted on the input piston? The two speed pump (input) has a piston of 2.66 in diameter for fast travel and of 0.54 in to exert larger forces. The switchover is accomplished by the build-up of hydraulic pressure against the load. What will the pressure in the hydraulic fluid be when each input piston is used?

15. If the pressure, using the small input piston is 4720 $lb/in^2$ on the press in the previous problem, what will the output force be if the output ram piston has a diameter of 5.05 in?

16. A standard tank of oxygen has a gauge pressure of 2200 $lb/in^2$ at 70°F. How many atmospheres of pressure is this?

17. A small block of lead weighs 4.45 lb. When it is suspended in water it appears to weigh 4.06 lb. What is the specific gravity of lead?

18. The acetylene line to a welding torch is regulated so the pressure is 6 $lb/in^2$. The oxygen line is set to carry 25 $lb/in^2$. If a mercury manometer were attached to these lines what difference in levels would there be for each line? How many bars, millibars and pascals of pressure in each?

ANSWER KEY (PROBLEMS)

Module P 2 FLUIDS I (STATICS)

1. No, molcules may be heavier.

2. Top, hydrometer sinks less in dense liquids to displace its own weight.

3. Pressure is force per unit area: N, N/m$^2$; dyne, dyne/cm$^2$; lb, lb/ft$^2$.

4. (a) pressure, (b) specific gravity, (c) pressure head, (d) atmospheric pressure head,

5. No, no.

6. About 76 cm, atmospheric pressure on mercury in open container pushes mercury up the tube into regions of low pressure until the weight of mercury in the tube balances the force of the atmosphere.

7. (a) Average pressure at sea level, 45° latitude and at 15°C (average temperature of earth), (b) 25 times atmospheric pressure, (c) 20 in Hg less than atmospheric (vacuum pressures are gauge pressures), (d) length of column of water that a given pressure will support or pressure in a stand-pipe, (e) pressure scale with the zero at standard atmospheric pressure, (f) station pressure plus pressure due to a vertical column from station to sea level.

8. 2.4 lb/yd$^3$, 1.43 kg/m$^3$, 12.9 lb

9. 1.24 kg/ℓ, 1.24, 206 lb

10. 10.4 lb/gal, 9.2 lb/gal, 1.25 kg/ℓ, 1.1 kg/ℓ, higher

11. $5.5 \times 10^5$, $8.6 \times 10^5$ N/m$^2$, 6.44, 9.50

12. 99 lb

13. 636 lb

14. 1080 lb, 194 lb/in$^2$, 4720 lb/in$^2$

15. 94 500 lb

16. 150 atm

17. 11.4

18. 12.2 in Hg, 51 in Hg, 0.41 bar, 410 mbar, $0.41 \times 10^5$ Pa, 1.72 bar, 1720 mbar, $1.72 \times 10^5$ Pa

EXPERIMENTS

Module P 2

## FLUIDS I (STATICS)

PURPOSE: The purpose of these experiments is (1) to study bouyancy of objects submerged in liquids, calculate the specific gravity of various solids and liquids and check the specific gravity of an unknown liquid using the hydrometer; (2) to study pressure in a balloon by measuring it with a manometer and plot a hysteresis curve (pressure-volume) as the balloon is inflated and then deflated.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

## EXPERIMENT I SPECIFIC GRAVITY

INFORMATION: Specific gravity is defined by equation 5 in the Information Sheets of this booklet:

$$\text{Sp gr} = \frac{Ds}{Dw} \qquad 5.$$

Where Ds is the density of the substance and Dw is the density of water. Specific gravity can also be found by dividing the weight of any sized sample of the substance by the weight of an equal volume of water.

When an object is submerged in water, the bouyancy is equal to the weight of an equal volume of water which is also equal to its loss of weight in water. So the specific gravity of a solid object can be found by equation 6:

$$\text{Sp gr of solid} = \frac{\text{weight in air}}{\text{loss of weight in water}}$$

The specific gravity of an unknown liquid can be found by submerging an object both in the liquid and in water, its specific gravity is:

$$\text{Sp gr of liquids} = \frac{\text{loss of weight in liquid}}{\text{loss of weight in water}}$$

Specific gravity or density tables can be found in your textbook on the pages given below. Recall that specific gravity is numerically equal to the density in grams per cubic centimeter. If the density is given in kilograms per cubic meter, move the decimal three places to the left. If it is given in pounds per cubic foot, divide by 62.4.

| | |
|---|---|
| Introductory Applied Physics: | page 241 |
| Elements of Physics: | page 157 |
| Physics for Career Education: | page 190 |
| Physics for Technology; | page 59 |
| Modern Technical Physics: | page 198 - 199 |

EQUIPMENT:

1. Harvard trip balance mounted on stand
2. Light string or thread
3. Three specific gravity specimens (Sargent-Welch #1158)
4. Two beakers (600 ml)
5. Cylinder
6. Quantity of unknown liquid
7. Hydrometer (Sargent-Welch #5-42035-C)

Check to see that all the equipment is available before you start. Ask your instructor if you have any questions about it. Obtain a data sheet from the instructor.

NOTE: The hydrometer is very fragile and is stored separate from the rest of the equipment. When you are ready to use it (step 14) the instructor will get it for you.

PROCEDURE:

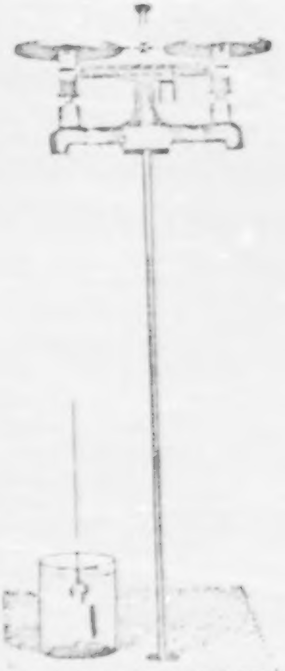
1. Mount the Harvard trip balance on the stand. See the accompanying figure. NOTE: A shorter stand with a tripod base is used.

2. Make a loop from the light string or thread (about 6 in diameter). Attach the loop to the hook on the underside of the balance.

3. Fill one beaker with water; the other beaker with the unknown liquid. Fill them to about the 400 ml level.

4. Attach the aluminum specimen to the string and weigh it first in air, then submerged in water, then submerged in the unknown liquid. Record on the data sheet (table 1). NOTE: It is essential that the specimen be dry before each reading. Use paper towels.

5. Attach the brass specimen and repeat step 4.



The balance has a socket to permit supporting it on the upright rod. A small hook extends below the base under the balance pan.

By permission: Sargent-Welch Scientific Company

6. Attach the iron specimen and repeat step 4.

7. Calculate the loss of weight of each specimen in water and in the unknown liquid. Record in table 2 on the data sheet. Note that each line in table 2 is the weight of equal volumes of the metal, water and unknown liquids.

8. Calculate the specific gravity of each specimen and record in table 3 on the data sheet. (Use equation 6).

9. Look up the specific gravity for each metal in tables in your textbook and record in table 3.

10. Calculate the error between the calculated value and table values for each metal.

11. Calculate the specific gravity of the unknown liquid and record in table 4 on the data sheet. (Use equation 7).

12. Calculate the average specific gravity for the three values in table 4.

13. Fill the cylinder with the unknown liquid (5 cm from top).

14. Obtain a hydrometer from the instructor and use it to measure the specific gravity of the unknown liquid. CAUTION: Use the hydrometer with care. It is very fragile.

15. Calculate the error between the calculated average value and the hydrometer value of the specific gravity of the unknown liquid.

16. Clean up the beakers, cylinders and specimens. Return the hydrometer to the instructor. Use paper towels for clean-up. Put everything back in the proper drawer.

## EXPERIMENT II THE MANOMETER

EQUIPMENT:

1. Balloon (new)
2. Two manometers (water and mercury)
3. Shut-off valve
4. Rubber band
5. One-half meter stick

CAUTION: Do not inflate the balloon except as described below. The rubber will stretch and your readings will not show a hysteresis curve.

PROCEDURE:

1. Attach the balloon securely to the valve with a rubber band.

2. Atach a clean sterilized mouthpiece to the other end of the valve.

CAUTION: Only one person should inflate the balloon with the mouthpiece. They have been boiled to prevent the spread of germs.

3. Inflate the balloon through the valve to a diameter of about three inches. Do not inflate too much, then deflate. One person can measure as the other inflates the balloon. NOTE: Measure the balloon along its greatest diameter.

4. Attach the balloon to the water manometer: Lightly pinch the hose and attach. Move the hose back and forth until the manometer levels are equal.

CAUTION: Do not pinch the balloon when it is attached to the manometer. The pressure will blow the water out of the tube. If you should lose any of the water, call the instructor to refill.

5. Open the valve and record the difference in levels of the water in the manometer. At the same time, record the diameter of the balloon.

6. Remove the apparatus from the manometer and inflate the balloon to about 5 in (largest diameter). Reattach it to the water manometer, open the valve, read and record the difference in levels and the diameter.

7. Repeat step 6 several times for balloon diameters of about 7 in, 9 in and 11 in. Do not exeed 11 in (largest diameter) or the balloon will pop.

8. Repeat step 6 several times (except deflate the balloon) for diameters of about 9 in, 7 in, 5 in and 3 in.

9. Reinflate the balloon to about a 6 in diameter. Record the pressure head (water).

10. Calculate the pressure in dynes/cm$^2$. $P = (980 \text{ cm/sec}^2)(1 \text{ g/cm}^2)h$.

11. Using the pressure calculated in step 10, calculate the pressure head for a mercury manometer. See tables in your textbook for density.

12. Transfer the balloon to the mercury manometer and record the difference in levels.

13. Compare calculated and measured mercury pressure heads.

14. Plot a graph of the data obtained in steps 6 through 8 to obtain a hysteresis curve. Plot pressure vs diameter.

15. Question: Does the manometer read absolute or gauge pressure? Explain.

16. Use paper towels to clean up if necessary and put everything away in the proper drawer.

2

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE – Milford Campus Milford, Nebr. 68405

Module: P 3

Title: FLUIDS II (DYNAMICS)

Module Contents:
1. Rate of flow
2. Velocity of flow
3. Bernoull's principle
4. Viscosity
5. Hydraulic valves and circuits

Program: This module has been prepared expecially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to continue the study of the principles of hydraulics. These principles are used in various lubrication, cooling, clamping, reciprocal motion and other power and control equipment in the manufacturing industries. This module also serves as an introduction to courses in fluid power.

Producer: Gene Waring

Date Produced: January 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module P 3 FLUIDS II (DYNAMICS)

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define rate of flow (volumetric).
2. State a formula for rate of flow in terms of the velocity of flow.
3. Define pressure head, velocity head and friction head and relate these quantities to the total head.
4. State the formula for velocity head.
5. Distinguish between streamline and turbulant flow.
6. State Bernoulli's principle in words only in terms of high and low velocities and high and low pressure.

7. Describe a venturi meter and use one to measure the rate of flow of liquids (or gases) through it.
8. Describe how a siphon works.
9. Describe various applications of Bernoulli's principle.
10. Describe how needle, check, pressure relief, sequencing and directional control valves work.
11. Use the DIGIAC 844 training console to set up various hydraulic circuits to investigate the function of the valves in objective 11, given a circuit diagram.
12. Solve various problems using the definitions and formulas in objectives 1, 2, 3 and 4.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of fluid dynamics. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbooks plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N. C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 11, sections 11.13-11.21, pages 282-295 and chapter 12, sections 12.21, pages 314-316.

C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 13, sections 13.1-13.5, pages 167-173.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden. L., Prentice-Hall Inc., 1st ed., 1974. This text does not include the subject of fluid dynamics. See Information Sheets (A).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 13, sections 13.8-13.10, pages 202-212.

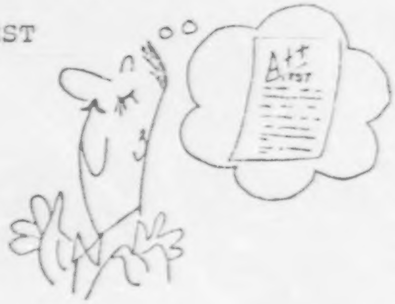
F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 14, sections 14.5-14.6, pages 220-225.

II. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving fluid dynamics problems. The problems from number five on are applied to your technology.

III. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

IV. Performing Laboratory Experiments: There are two experiments in this module. They will give you practice in learning about fluid dynamics and hydraulic circuits. Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (P 3) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

## TEST



You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module P 3 FLUIDS II (DYNAMICS)

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Total head = pressure head + velocity head + friction head.

T - F 2. The velocity of flow out of a hole in the bottom of a tank depends on the size (area) of the hole.

T - F 3. Eddy currents are found in streamline flow only.

T - F 4. A check valve is one in which flow is allowed to proceed one direction only.

T - F 5. Fluids always moves from regions of high pressure to regions of low pressure.

6. Fluid flows at a rate of 2.5 $\ell$/s in a pipe of 1.5 cm diameter. Its velocity in meters per second is:

a) 44.2
b) 14.1
c) 22.6
d) 1.67

7. If the rate of flow of air in a duct is 800 $ft^3$/min, how many cubic feet will pass a point in 3.5 hr?

a) 230
b) 2800
c) 168 000
d) 16 800

8. If 5000 gal of gasoline can be unloaded from a transport truck in 29 min and the unloading pipe is 3 in in diameter what is the average velocity of the gasoline in the pipe? (1 gal = 231 $in^3$).

ANSWER KEY TO THE SELF-EVALUATION TEST

Module P 3 FLUIDS II (DYNAMICS)

| Question-Answer | If you missed this question, you are directed to these learning activities |
|---|---|
| 1. T | I Reading or III Problems |
| 2. F | I Reading |
| 3. T | I Reading |
| 4. T | V Experiment #2 |
| 5. F | I Reading or V Experiment #1 |
| 6. b | III Problems |
| 7. c | III Problems |
| 8. 7.8 ft/s | III Problems |

INFORMATION SHEET

Module P 3 FLUIDS II (DYNAMICS)

When a faucet is turned on in the home, water begins to move. It may be moving at a relatively high speed at the faucet and in the pipes leading to it. Back in the large underground mains, however, the change in speed may be barely noticable. Even so, there is an enormous amount of water that has begun to move, from the faucet all the way back to the stand-pipe or pumps. Water in pipes that may be several miles long must start moving. Pressure exerted by the pump or by the liquid column in the stand-pipe must provide the force necessary to accelerate the water.

NOTE: If the rate of flow is 5 gal/min, water will move at about 3.4 ft/min in 6 in mains. About 6.5 tons of water will be moving at this speed for each mile of 6 in main back to the pumping station.

Turning the faucet off creates a problem, also. Tons of moving water must be stopped. To prevent the pipes from "banging", an impact absorbing device must be installed. This is an air chamber into which the flow can be diverted to absorb the flow energy.

As you can see the inertia of fluids plays and important part in fluid dynamics. Friction, also, plays an important role in the flow of liquids and gases in pipes, ducts and other conduits. Friction depends on the size of the pipe, the smoothness of the inner surface of the pipe, the number of bends and turns the pipe makes, and the resistance to flow of the fluid itself.

The property of fluids that tend to resist flow is called viscosity. The layer of molecules touching the inner surface of a pipe will adhere to it. These molecules do not move. The next layer sticks to the first layer by cohesive forces. A few molecules in the second layer slip past those in the first. There is more movement in the third layer and even more in the fourth. This continues to the center of the pipe where the fluid is moving at its fastest speed.

If the molecules of a liquid have a strong cohesion for each other, there will be a strong resistance to flow and they have a high viscosity. "Heavy" oils are examples of high viscosity liquids. The viscosity of a given liquid will increase as temperature decreases. Viscosity is important in lubrication and in cross-country oil and gas pipelines.

If the velocity of flow becomes too great, eddy currents will form and the flow becomes turbulant. The amount of friction is increased in turbulant flow as compared to streamline flow. A molecule moves past a certain point and then follows a certain path from then on. If the flow is streamline, all other molecules that pass through the same point will follow exactly the same path as the first one. This does not happen in turbulant flow.

RATE OF FLOW

The volumetric rate of flow (Q) must be distinguished from the speed of flow. In a given pipe the rate of flow must be constant. This is true since there is no place for the fluids to pile up. In figure 1, if 5 gal flow past point a in 1 min, then 5 gal must flow past point b in 1 min.

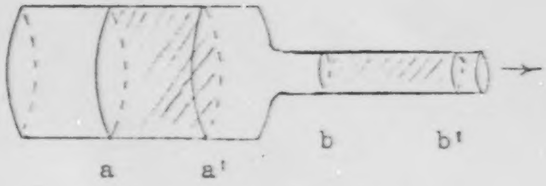


Fig 1. Liquid flow in a pipe

The rate of flow is defined by the formula:

$$Q = \frac{V}{t} \qquad 1.$$

Where V is the volume flowing past a given point in time t. Its common units are gal/min, $ft^3/s$, ℓ/s, $m^3/s$, acre-ft/hr, etc.

Suppose and imaginary cross-section at point a in figure 1 moves to point a'. The cylinder of liquid between the points has a volume $V_a = A_a s_a$ where $A_a$ is the cross-sectional area at point a and $s_a$ is the distance between a and a'. The rate of flow from equation 1 becomes: $Q = A_a s_a/t$. The quantity $s_a/t$ is the speed of flow $(v_a)$. So equation 1 becomes:

$$Q = Av \qquad 2.$$

Since the rate of flow at point a must equal the rate of flow at point b, then:

$$A_a v_a = A_b N_b \qquad 3.$$

Since $A_b$ is smaller than $A_a$, then $v_b$ must be larger than $v_a$ for the products to be equal. Note that the speed of flow is greater in smaller pipes but the rate of flow is the same.

BERNOULLI'S PRINCIPLE

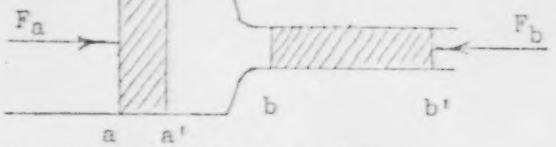


Fig 2.Bernoulli's principle

If the law of conservation of energy (work equation) (see module M 8) is applied to the liquid in the pipe of figure 2, the equation becomes:

$$\tfrac{1}{2}m\, v_b^2 - \tfrac{1}{2}m\, v_a^2 = (F_b - F_a)s$$

m is the mass of water between a and a' or b and b'. $F_a$ is the force on the mass of water at a and $F_b$ is the force on the mass at point b'. If this equation is rearranged and each term devided by the volume of water in each section it becomes:

$$P_a + \tfrac{1}{2}dv_a^2 = P_b + \tfrac{1}{2}dv_b^2 \qquad 4.$$

Where P is the pressure, d is the density and v is the velocity. The second term on each side of the equal sign is the kinetic energy per unit volume (ft lb/ft$^3$, J/m$^3$ etc.). It has the same units as pressure (lb/ft$^2$, N/m$^2$, etc.).

Notice that $v_b$ is greater thatn $v_a$. This means that $P_b$ must be less than $P_a$ for the two terms on both sides to have the same sum. Equation 4 is Bernoulli's principle and is derived from the work equation. In words it is:

> Bernoulli's principle: In streamline flow of fluids in pipes or ducts, at points where the velocity is high the pressure is low, and at points where the velocity is low the pressure is high.

Equation 4 would have to include the gravitational potential energy per unit volume on each side if the vertical levels of points a and b were different. Bernoulli's principle is true only if there is no loss of pressure due to friction between the two points.

PRESSURE HEAD

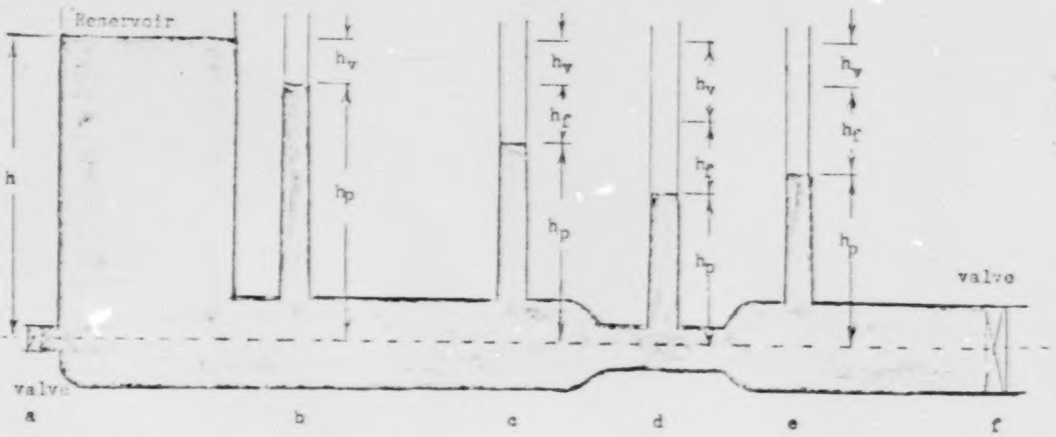


Fig 3. Velocity head + friction head + pressure head = total head.

The water level in the reservoir in figure 3 is maintained with a total pressure head h. Valves are located at points a and f. If both valves are closed the level of the water in manometer tubes b,c,d,and e will be the same as in the reservoir. If valve a is opened, water runs out. The speed (v) of the stream at the valve is given by the formula:

$$v = \sqrt{2gh} \qquad 5.$$

Where g is the acceleration of gravity. The velocity of the stream is called the velocity of efflux. This formula is derived from a more complex form of Bernoulli's principle (equation 4).

Example: If the reservoir level is 100 ft above the valve at a, find the velocity of efflux at the valve. If the open valve forms a circular opening with a ½ in radius, find the rate of flow.

Given: $h = 100\ \text{ft}$
$g = 32\ \text{ft/s}^2$
$r = 0.5\ \text{in} = 0.0417\ \text{ft}$

Solution: $v = \sqrt{2(32\ \text{ft/s}^2)(100\ \text{ft})} = 80\ \text{ft/s}$
$Q = Av = (\pi r^2)v$ (equation 2)
$= \pi(0.0417\ \text{ft})^2 \cdot (80\ \text{ft/s})$
$= 0.436\ \text{ft}^3\text{/s}$
$= 3.26\ \text{gal/s}$

Example: How much water, in the previous example, will run out in 5 min?

Given: $Q = 3.26\ \text{gal/s}$
$t = 5\ \text{min} = 300\ \text{s}$

Solution: $V = Qt$ (equation 1)
$= (3.26\ \text{gal/s})(300\text{s}) = 978\ \text{gal}$

Note that if valve a was some distance away on the end of a pipe, the pressure head would be reduced because of friction. This would reduce both velocity and rate of flow.

Refer to figure 3 again. If valve a is closed and valve b is opened, the water levels in manometer tubes b,c,d and e change. Tube b is assumed to be close to the reservoir so there is no friction loss. However, Bernoulli's principle suggests there will be lower pressure because the water is moving at point b in the pipe. The pressure head ($h_p$) is lower than the total pressure head by an amount ($h_v$) called the velocity head. The velocity head can be calculated by equation 5 if the velocity is known.

$$h = \frac{v^2}{2g} \qquad 6.$$

Tube c shows the same velocity head loss as point b since the velocity of the water in the pipe is the same. Since tube c is further away from the reservoir, there is an additional loss of pressure due to friction called the friction head ($h_f$). Note that the total head equals the pressure head plus the velocity head plus the friction head:

$$h = h_p + h_v + h_f \qquad 7.$$

Tube d is in a narrow section of the pipe where the velocity is greater. Since the velocity head has increased the pressure head is less. At point e the velocity head has changed back to what is was at point c. The pressure head is less at e than at c because the friction head has increased with the distance from the reservoir.

Example: Find the pressure head at point e if the total head is 100 cm. The friction head is 72 cm and water is flowing at a rate of 1.2 ℓ/min. The tube has a 0.8 cm radius.

Given:
$p = 100$ cm
$p_f = 20$ cm
$Q = 1.2$ ℓ/min $= 20$ cm³/s
$r = 0.8$ cm

Solution:
$v = Q/A = Q/\pi r^2$
$= (20 \text{ cm}^3/\text{s})/\pi(0.8 \text{ cm})^2$
$= 9.95$ cm/s
$h_v = v^2/2g = (9.95 \text{ cm/s})^2/2(980 \text{ cm/s}^2)$
$= 0.01$ cm
$h_p = h - h_v - h_f$
$= 100 \text{ cm} - 0.01 \text{ cm} - 72 \text{ cm} = 28 \text{ cm}$

Example: Find the pressure head at point d for the previous problem Assume the friction head is the same. The radius of the pipe at d is 0.4 cm.

Given:
$r = 0.4$ cm
$Q = 20$ cm³/s

Solution:
$v = (20 \text{ cm}^3/\text{s})/ (0.4 \text{ cm})^2$
$= 39.8$ cm/s
$h_v = (39.8 \text{ cm/s})^2/2(980 \text{ cm/s}^2)$
$= 0.8$ cm/s
$h_p = 100 \text{ cm} - 0.8 \text{ cm} - 72 \text{ cm} = 27.2 \text{ cm}$

Notice that the pressure head differs by about 0.8 cm at points d and e and is less at point d.

VENTURI METER

The constriction at point d in figure 3 is known as a venturi. The throat of a carborator on an automobile is an example. When manometers (or pressure gauges) are located at points d and e the device is known as a venturi meter and can be used to measure the rate of flow of the fluid through it.

Using equation 6 to find the difference in the velocity head at the two points and substituting the ratio Q/A for v the equation formed becomes:

$$Q = A_d A_e \sqrt{\frac{2\Delta P}{A_e^2 - A_d^2}} \qquad 7.$$

Where Δh is the difference in velocity heads. If there is no change in friction head between the two points then Δh is also equal to the difference in pressure head which is the difference in levels of the manometers.

In tems of pressure units equation 7 is:

$$Q = A_d A_e \sqrt{\frac{2\Delta h}{d(A_e^2 - A_d^2)}} \qquad 7a.$$

Where ΔP is the pressure difference and d is the density of the fluid.

SIPHON

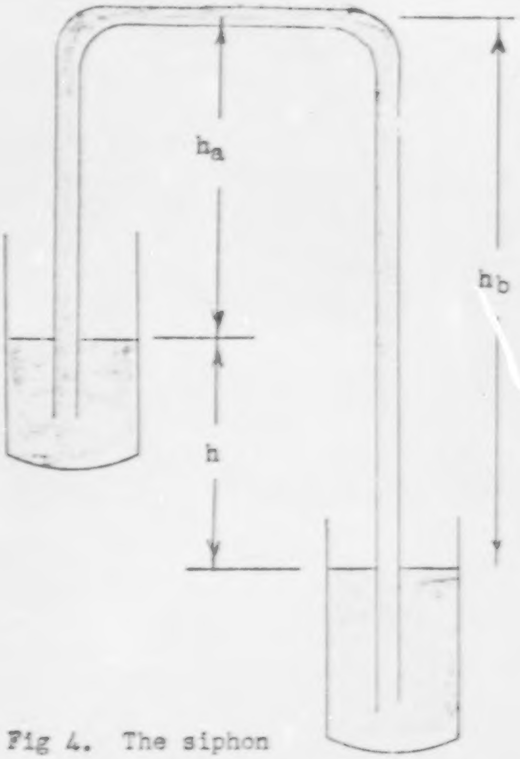


Fig 4. The siphon

The upper and lower basin in figure 4 are attached by a hose that acts as a siphon. The levels of liquid differ by a vertical distance h. If the distance h is not too great then h is the pressure head. Neglecting losses due to velocity and friction heads, the speed of flow is given by equation 5 and the rate of flow by equation 2. The distance from the level of the upper basin to the top of the siphon hose cannot exceed 34 ft since it is the atmospheric pressure that forces the water up the hose.

The force on the water in the hose at point A is one atmosphere minus $Dh_A$ and at point B it is one atmosphere minus $Dh_B$. The force on the water in the hose is greater at the upper level than at the lower end. Fluids will always flow from an upper level to lower.

HYDRAULICS

Objectives 10 and 11 refer to various hydraulic valves and equipment and to the DIGIAC 844 training console. Information about this equipment is included in the technical manuals that accompany this equipment. It will be made available to you as you use this equipment.

PROBLEMS

Module P 3 FLUIDS II (DYNAMICS)

1. Describe streamline flow. Discuss the behavior of particles following a particular path.

2. How does turbulant flow differ from streamline (laminar) flow? What are eddy currents. How does speed of flow affect turbulance?

3. How is total head, pressure head, friction head and velocity head related? What are some of the things that friction head depends on?

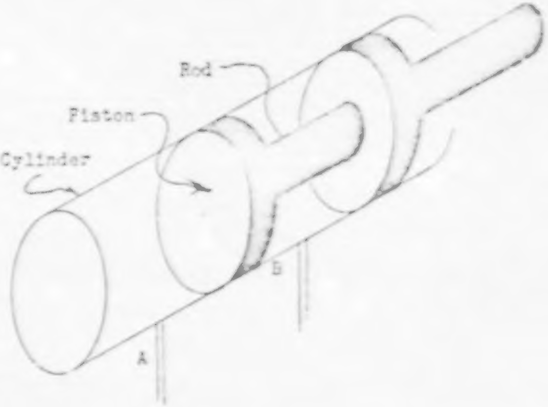
4. Define viscosity. How does friction head depend on it?

5. How is Bernoulli's principle related to the law of conservation of energy? Does the principle hold in fluid flow in which turbulant flow is present?

6. What is the pressure head in a hydraulic line in which the total head is 100 cm of mercury if the velocity head is 1.5 cm of mercury and the friction head is 37.4 cm of mercury?

7. A hydraulic cylinder has a piston with a 3½ in diameter and a 2 in rod as shown in the diagram. If the working pressure is 1250 $lb/in^2$, what force acts on the piston? What force acts on the piston during retraction?

8. The flow rate of the hydraulic fluid in the cylinder in problem 7 is 10 gal/min. At what speed will the piston move on the forward stroke? During retraction? What is the speed of the hydraulic fluid in the 0.75 in diameter hose from the pump?



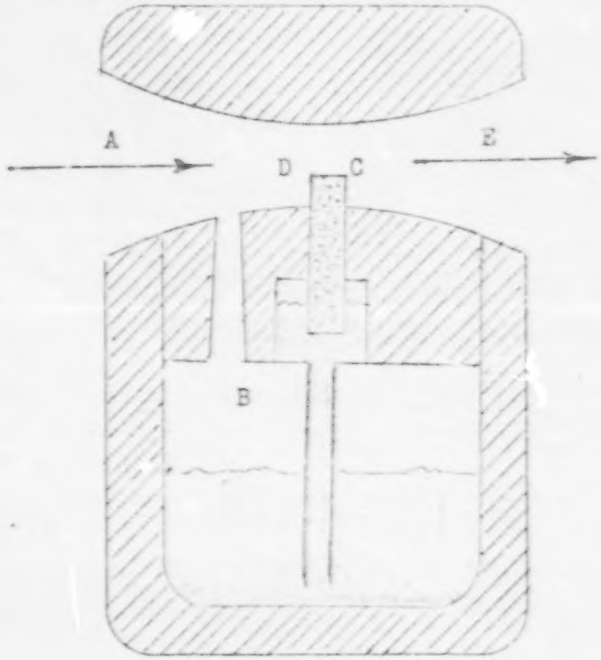
9. What is the rate of flow through a hydraulic line with a 0.5 in diameter if the velocity of flow is 20 ft/s? Express this rate in gallons per minute and liters per second. What is the velocity head in this hose?

10. In cutting ½ in steel with an acetylene torch, oxygen is used a a rate of about 90 $ft^3$/hr and acetylene at a rate of 12 $ft^3$/hr. Express the flow rate in liters per minute and in milliliters per second. What is the velocity of flow in the hoses if both have 0.25 in internal diameters.

11. Look up in welding resource books or texts to see how acetylene and oxygen are mixed in a welding torch. Draw a free-hand diagram of the cross-section of the mixing chamber for both balanced-pressure and injector type torches. Explain how each type works in a brief paragraph. Which one has a venturi and what does it do? What does the word "aspirate" mean?

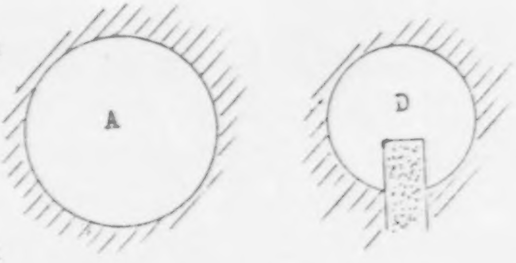
12. An above-ground storage tank at a manufacturing plant is nearly full of fuel oil. A hole 2 mm in diameter is located 2.5 m below the fuel level. What is the velocity of efflux and the rate of flow of the fuel spilling out of the hole? What volume will leak out in 10 min if the level doesn't change appreciably?

INFORMATION: In compressed air power equipment, the moving parts are lubricated by a fine oil mist introduced in the air line leading to the equipment. The mist is formed in a venturi that is connected into the air line. Air is introduced from the compressor and storage tanks by a hose connected at point A. (See accompanying diagram).



The pressure at point A is the pressure head at the compressor minus friction head in the hoses minus velocity head. At D (the venturi) the pressure is the pressure head minus the friction head minus a larger velocity head. Thus the pressure at D is less than at A. The pressure at A is transfered to the oil chamber (B) through a port and pushes the oil up the center tube where it comes in contact with an oil wick (usually a porous metal rod) at point C. Oil is then transfered to the top of the wick by capillary action and pressure from below. The wick extends into the air stream at the venturi section of the lubricator. The high velocity and lower pressure air moving past the wick allows it to pick off small droplets of oil forming an oil mist at point E on its way to the air powered equipment. The wick can be raised or lowered into the air stream or changed to one of courser or finer porosity to change the rate of feed.

13. The cross-section of the air stream at points A and D in the air-line lubricator decribed above are shown in the accompanying diagram. If the rate of flow of compressed air to a ½ in air drill is 4.12 $ft^3/min$, find the velocity of flow at points A and D. The diameter at A is 0.5 in and at C it is 0.4 in. The section of the wick extending into the stream of air at A is 0.15 x 0.075 in.

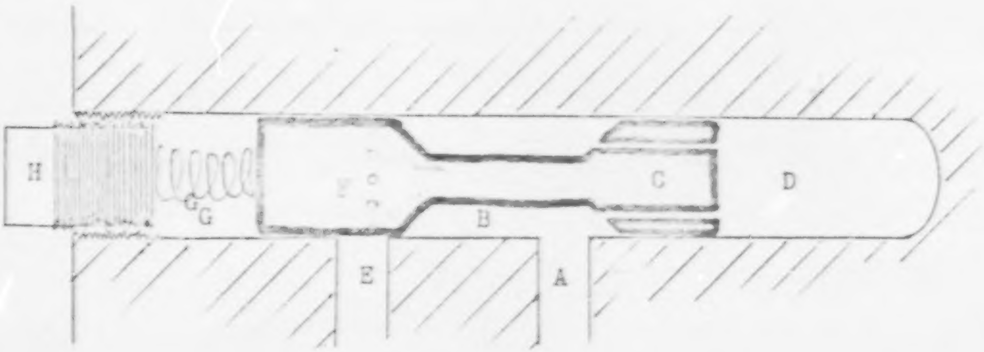


14. If the 4.12 $ft^3/min$ flow rate of 100 $lb/in^2$ compressed air corresponds to a flow rate of 28 $ft^3/min$ of free air, what volume of free air flows through the lubricator in the previous problem in 10 s? How many liters is this? How long would it take for 100 $ft^3$ of free air to flow through it?

15. Find the difference in pressure between points A and D in problem 13. The weight density of the compressed air is 0.55 $lb/ft^3$. The speed at point A is 50.5 ft/s and at D it is 86.4 ft/s. Hint: Use equation 4 (Information Sheets) and solve to get $P_a - P_b = \frac{1}{2} d(v_f^2 - v_a^2)$. Express the difference in pressure in inches of mercury and inches of water.

16. If the pressure difference created by the venturi in problem 15 is 0.29 $lb/in^2$, to what vertical height could the oil be raised? The weight density of the oil is 6.81 lb/gal.

INFORMATION:



A hydraulic pressure relief valve is pictured in the diagram. The liquid under pressure enters the valve at (A) filling the chamber (B). It also fills the chamber (D) by flowing through the channels in the piston at (C). Notice that the pressure in chamber (B) exerts forces on the piston is both directions and there is no net force on it. It is the pressure behind the piston in chamber (D) that causes the piston to move to the left.

The piston moves to the left, compressing the spring (G) until it exerts a force on the piston and just balances the force caused by the liquid pressure. The spring is adjusted so the entire piston moves left far enough that liquid can pass into the return port (E) thereby relieving the pressure. This reduces the pressure in chamber (D) and allows the piston to move to the right shutting off the flow to the return port. The piston thus repeats its movement to the left in short rapid strokes and maintains a fairly steady pressure in the hydraulic circuit behind port (A). Small holes in the piston at point (F) reduce valve clatter. The pressure in the circuit may be adjusted by turning the screw (H) which compresses the spring.

17. The diameter of a pressure relief valve described above is 0.75 in. The pressure is to be maintained at 20 $lb/in^2$.
    (a) What force compresses the spring? (This is the same as the force on the back of the piston).
    (b) The force calculated in part a moves the piston to the left 1/8 in, (and compresses the spring 1/8 in). What is Hooke's constant for this spring? Hooke's law: $F = ky$

18. It is required to change the valve in problem 17 so that it relieves at 35 $lb/in^2$ instead of 20 $lb/in^2$. How many turns of the screw must be made if the pitch is 1/16 in? (Pitch is the distance a screw moves inward during one complete turn). Hint: Calculate the force on the piston, due to liquid pressure, then calculate the distance this force would compress the spring. Remember that the piston can move only 1/8 inch so the difference must be made up by compressing the spring by turning the screw.

19. A small auxillary tank for emergency use is connected to the main tank by tubing with a 0.95 cm diameter. A shut-off valve in the connecting line is opened. If the level in the auxillary tank is 20 cm above that in the main tank, what is the rate of flow at that instant? Note that tubing connecting the bottoms of the tanks works the same as a siphon. A siphon, however, would not work at all without atmospheric pressure acting on the liquids in the two tanks.

20. Look up in your textbook or other source to find out the definition of the following units of pressure a) bar, b) millibar, c) pascal.

ANSWER KEY

Module P 3 FLUIDS II (DYNAMICS)

1. All particles passing through a given point in streamline flow will follow the same path.

2. Swirls or eddy currents form in turbulant flow. Flow may be streamline at slow speeds; turbulant at higher speeds.

3. $h = h_p + h \quad + h_f$, viscosity, inner surface of pipe, turns and bends in the pipe, speed of flow etc.

4. Friction head is greater in fluids of higher viscosity.

5. Bernoulli's principle is a spedial case of the law of conservation of energy. No.

6. 61.1 cm Hg.

7. 12 000 lb, 8100 lb

8. 4 in/s, 5.9 in/s, 7.3 ft/s

9. 0.0273 $ft^3/s$, 12.2 gal/min, 0.77 ℓ/s, 6.25 ft of oil.

10. 42.5 ℓ/min, 708 mℓ/s, 5.7 ℓ/min, 94 mℓ/s, 73 ft/s, 9.8 ft/s

11. For example see: Sacks, R.J., Welding Principles and Practices, C.A. Bennett Co., 1976, page 160.

12. 7 m/s, 22 mℓ/s, 13.2 ℓ

13. 50.5 ft/s, 86.4 ft/s
14.
14. 4.67 $ft^3$, 132 ℓ, 3.57 min

15. 0.29 $lb/in^2$, 0.6 in Hg, 8.1 in $H_2O$

16. 9.9 in

17. 8.84 lb, 70.7 lb/in

18. 1.5 turns

19. 140 mℓ/s

20. See text

## Module P 3 FLUIDS II (DYNAMICS)

PURPOSE: The purpose of these experiments is (1) to study Bernoulli's principle as it applies to the flow of a liquid through a venturi tube and (2) to use the DIGIAC 844 training console to investigate the function of various valves and hydraulic circuits.

CAUTIONS:

1. Read all the instructions before handling any of the pieces of equipment.

2. Never interfere with an experiment someone else is performing or with the equipment they are using.

3. Observe all cautions listed in the procedure section of these instructions.

## EXPERIMENT I BERNOULLI'S PRINCIPLE

EQUIPMENT: Check to see if all the following equipment is available before you start. If you have any questions about it ask the instructor.

1. Mounted venturi tube with two manometer tubes
2. One constant level tank
3. Stand with tripod base (1 m long or more)
4. Hose
5. Sink for catch basin and drain
6. One 4 ℓ beaker
7. One 2 ℓ beaker
8. Timer
9. Caliper (vernier)

PROCEDURE: Obtain a data sheet from the instructor.

NOTE: Three students are required to perform this experiment. One student will pour water into the constant level tank. The second student will read the manometer and operate the timer. The third student will catch water as it flows out the end of the venturi tube.

CAUTION: Use care to avoid breakage of glassware.

1. Insert the rubber stopper with hose attachment to the left end of the venturi tube. The other rubber stopper goes in the right end pointed slightly downward. Water comes out the hole in the rubber stopper and into the sink.

2. Mount the constant level tank on the stand and connect it to the venturi tube with the rubber hose. The tank should be about 1 m above the tube.

3. Set the apparatus in a position so water coming out of the tube will flow into the sink.

4. Student #1 should fill the 4 ℓ beaker with water and practice pouring it into the tank. Try to maintain a constant level within an inch of the top. Once you begin don't allow the water to empty out of the tank. A new beginning will be required if air gets into the hose. (See next step.) If you run low of water, student #3 can fill it for you with the 2 ℓ beaker. Use care to avoid water spillage. Clean up with paper towels.

5. Once water begins to flow, student #2 should hold his fingers over the ends of the manometer tube and tilt the apparatus back so the air is revoved from the venturi and manometer tubes. Use care so the water continues to flow into the sink.

6. After the air is removed, student #3 should see that student #1 has at least 3 ℓ of water. If necessary pour some into his container.

7. Once constant level is maintained, student #3 should place his empty, dry beaker under the stream. At the same time student #2 should start the timer and record both manometer readings.

8. After about 2 ℓ of water has been caught by student #3, he should remove it from the stream. At the same time, student #2 should stop the clock. Student #1 may then stop pouring water into the tank.

9. Measure the water in the 2 ℓ beaker as accurately as you can. Record the volume and the time. These two quantities determine the rate of flow.

10. Use the vernier caliper to measure the inside diameter of the venturi tube at the right end. NOTE: The right and left ends have the same diameter so it is not necessary to dismantle the apparatus.

11. Calculate the area of the venturi tube at the right end.

12. Calculate the rate of flow. Use information from step 9.

13. When equation 7 (Information Sheet) is solved for $A_b$ it becomes:

$$A_b = QA_a\sqrt{\frac{1}{Q^2 + 2g\Delta hA_a^2}}$$

Use this equation to solve for the cross-sectional area at the narrow part of the venturi tube. NOTE: Make sure all units are cgs: (Q-cm$^3$/s, A-cm$^2$, and $g = 980$ cm/s$^2$.

14. Use the formula for the area of a circle to determine the diameter of the narrow part of the venturi tube.

15. The measured diameter of the narrow section is 0.74 cm. At the point where the manometer tube is attached, there is a flare which increases the size of the tube where pressure is measured. The flare adds about 30% to the diameter of the tube (0.95 cm). Compare your calculated diameter (step 14) to this value.

16. Calculate the velocity of flow at points b and c.

17. Clean up all spilled water with paper towels. Return the equipment to the proper box or drawer.

## EXPERIMENT II DIGIAC 844 TRAINER

EQUIPMENT:

1. DIGIAC 844 training console
2. Various quick-connect hoses, tees and valves
3. Procedure handbooks

PROCEDURE: Obtain a data sheet from the instructor and a procedure handbook, There are seven experiments. Each experiment is accompanied by a hydraulic circuit diagram and instructions (test procedure).

1. Set up the hydraulic circuit according to the circuit diagram.

CAUTION: BE SURE TEST CONSOLE IS TURNED OFF WHEN MAKING CONNECTIONS.

2. Investigate the circuit by following the test procedure step by step.

3. Write down your observations on the data sheet at each test procedure step.

4. The following is a list of the experiments you should perform. These experiments require about 50 min of time. Three students should work together, taking turns setting up and operating the hydraulic circuits.

    1. Pressure: Investigates how pressure is created.
    2. Flow: Investigates how flow is created by a pump.
    3. Check Valves: Investigates the function of check valves.
    4. Pressure Relief Valve: Studies the function of pressure relief valves.
    5. Pressure Sequencing Valve: Studies the function of pressure sequencing valves.
    6. Directional Control Valve: Studies the function of a directional control valve.
    7. Directional Control Valve: Studies the function of a 3-position closed-center directional control valve.

5. Use paper towels to clean up the oil after you are finished and put everything away.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: P 4

Title: Structure of Matter

Module Contents:
1. Sub-atomic particles
2. Structure of the atom
3. Periodic chart
4. Molecules
5. Kinetic theory of gases
6. Properties of matter

Program: This module has been prepared especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to introduce the concepts of atoms and molecules and their structure. This module provides a basis for and understanding of properties of matter, especially the thermal properties that are introduced in the next few modules. This module is a prerequisite for those modules on Heat.

Producer: Gene Waring

Date Produced: February 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module P 4 MOLECULAR PROPERTIES OF MATTER

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Distinguish between homogeneous and heterogeneous substances, between elements and compounds and between solids, liquids and gases.

2. Define atom and molecule.
3. Distinguish between electrons, protons and neutrons in terms of electrical charge, mass and volume.
4. Define atomic number and atomic mass and state how the number of neutrons in an atom is related to these quantities.
5. Describe the planetary model of the atom.
6. Use the periodic chart to determine the number of protons and neutrons in the nucleus and the number of orbits containing electrons and the number in each orbit for a given atom.
7. Describe ionic and polarization bonding.
8. Describe adhesion, cohesion, surface tension, capillarity and crystal structure.
9. Solve problems involving surface tension and capillarity.
10. State the kinetic and molecular theory of gases.
11. Describe diffusion, osmosis, gas pressure, and the cooling effect of evaporization and sublimation.
12. Solve problems involving the relationship between the temperature of a gas and the speed of the molecules.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, matching and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of molecular structure. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper, page 6) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper, page 8) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper, page 5).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper (page 9). The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read all of chapter 9, pages 227-237, and chapter 34, sections 34.1-34.8, pages 927-934.

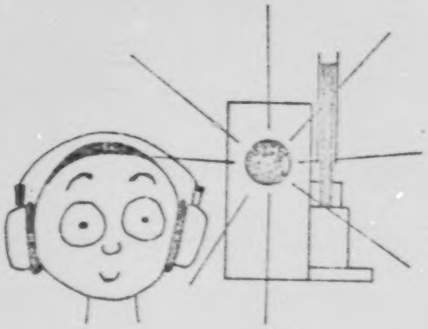
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 12 sections 12.10-12.12, pages 159-163, chapter 48 sections 48.1-43.3 pages 617-621 and chapter 14 section 14.1-14.3 pages 180-183 and sections 14.9-14.12 pages 188-192.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 14, sections 14.1-14.5 pages 183-189. Also see Information Sheet (A).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 30, section 30.3, pages 614-615, chapter 13 section 13.7 pages 197 -201, chapter 15 section 15.3, page 242 and section 15.6 pages 250-251. Also see Information Sheet (A).

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chaper 35, section 35.1, pages 583-585, chapter 36 all except section 36.2. Chapter 37 section 37.1-37.3 pages 621-625, and chapter 18, sections 18.6-18.8, pages 282-291.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Maxwell Speed Distribution, (BFA-Ealing 80-291)

B. Random Walk and Brownian Motion, (BFA-Ealing 80-292)

C. Properties of Gas, (BFA-Ealing 80-296)

D. Diffusion, (BFA-Ealing 80-295)

E. Evaporation Causes Cooling, (Doubleday Multimedia 13075)

F. Liquids Evaporate, (Doubleday Multimedia 13025)

G. Bubble Model of a Crystal-Structure and Boundries, (BFA-Ealing 84-011)

H. Bubble Model of a Crystal-Deformation and Dislocations, (BFA-Ealing 84-012)

I. Drops and Splashes, (BFA-Ealing 82-0076)

NOTE:Film B shows Brownian motion for a few seconds at the end of the film. Film I is especially good.

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving problems about properties of matter.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is no experiment in this module.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module P 4 MOLECULAR PROPERTIES OF MATTER

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page. DO NOT WRITE ON THIS TEST.

A Electron
B Proton
C Element
D Compound
E Cohesion
F Adhesion
G Diffusion
H Evaporation
I Homogeneous
J Heterogeneous

Match each of the following statements with the terms listed above. NOTE: Some may be used twice; some not at all.

__________ 1. A substance composed of only one kind of atom.

__________ 2. The forces that make solder bond to copper.

__________ 3. A discription of a substance that appears to be pure.

__________ 4. A discription of a substance in which the presence of more than one kind of material is apparent.

__________ 5. Fish odors spread easily to other foods in a refrigerator.

__________ 6. Of three sub-atomic particles, this one has the least mass.

__________ 7. A substance whose base particles are made up of more than one kind of atom.

__________ 8. A force between molecules of the same kind.

__________ 9. A sub-atomic particle with a positive charge.

__________ 10. Gasoline emits a gaseous vapor, even below the boiling point.

T - F 11. Sodium is in the 3rd period (row) and the 1A column of the periodic chart. It therefore has one electron in its outer orbit.

T - F 12. A discription of sodium is shown in the box. It has 12 protons and about 11 neutrons.

11
Na
22.9898

T - F 13. A compound is made up of atoms of a single kind.

T - F 14. Capillary action causes molecular structure to break down.

T - F 15. Diffusion is much slower paced in liquids than it is in gases.

T - F 16. A positive ion is an atom that has gained electrons.

T - F 17. When a liquid evaporates, it is the high speed molecules that escape. This reduces the temperature of the remaining liquid.

T - F 18. The pressure of a gas can be increased by reducing the volume of the gas.

T - F 19. The average kinetic energy of the molecules of a gas depends on the pressure of the gas.

T - F 20. In gases, the molecules are far enough apart that cohesive forces are ineffective.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module P 4 MOLECULAR PROPERTIES OF MATTER

| Question-Answer | | If you missed this question, you are directed to these learning activities |
|---|---|---|
| 1. | C | I Reading and/or II Listening/Viewing |
| 2. | F | I Reading and/or II Listening/Viewing |
| 3. | I | I Reading and/or II Listening/Viewing |
| 4. | J | I Reading and/or II Listening/Viewing |
| 5. | G | I Reading and/or II Listening/Viewing |
| 6. | A | I Reading and/or II Listening/Viewing |
| 7. | D | I Reading and/or II Listening/Viewing |
| 8. | E | I Reading and/or II Listening/Viewing |
| 9. | B | I Reading and/or II Listening/Viewing |
| 10. | H | I Reading and/or II Listening/Viewing |
| 11. | T | III Solving problems |
| 12. | F | III Solving problems |
| 13. | F | I Reading, III Listening/Viewing and/or III Solving problems |

| | | |
|---|---|---|
| 14. | F | I Reading, III Listening/Viewing and/or III Solving problems |
| 15. | T | I Reading, III Listening/Viewing and/or III Solving problems |
| 16. | F | I Reading, III Listening/Viewing and/or III Solving problems |
| 17. | T | I Reading, III Listening/Viewing and/or III Solving problems |
| 18. | T | I Reading, III Listening/Viewing and/or III Solving problems |
| 19. | F | I Reading, III Listening/Viewing and/or III Solving problems |
| 20. | T | I Reading, III Listening/Viewing and/or III Solving problems |

## INFORMATION SHEET

## Module P 4 MOLECULAR PROPERTIES OF MATTER

Any sample of matter can be classified as either *impure* or *pure*. When a sample of material is broken down to base particles (molecules), almost all of the particles will be of one kind if the material is a pure substance. An impure substance (mixture) consists of two or more kinds of base particles.

Pure substances are subdivided into two kinds: *elements* and *compounds*. The base particles or molecules of elements are made up of only one kind of atom. Compounds have base particles that are made up of more than one kind of atom.

Impure samples of matter can either be *heterogeneous* or *homogeneous*. You can easily tell when the sample is heterogeneous. You can see at least two kinds of substances mixed together. A mixture of peanuts, cashews, almonds, etc.(party mix) is heterogeneous, a mixture of dry coffee grounds and sugar crystals is also heterogeneous. When the particles become smaller it is more difficult to distinguish the dissimilar particles (dry cocoa and powdered sugar, for example). It would be even more difficult to distinguish powders of the same color such as powdered sugar and wheat flour. Magnifying glasses or microscopes would help to see the different particles. Heterogeneous mixtures can usually be separated mechanically into their separate components.

Other mixtures are said to be homogeneous. You cannot tell that there is more than one substance present even with powerful microscope. Gasoline, antifreeze solutions, a cup of coffee, battery electrolytes, pepsi cola etc. are examples of homogeneous mixtures. Homogeneous mixtures require sophisticated methods such as distillation to separate the materials. Liquids and gases are usually homogeneous elements and compounds are homogeneous substances.

*Molecules* are the smallest particles of a substance that has all the basic properties of that substance. Note that it is entirely correct to speak of molecules of an element. *Atoms* are the smallest particle that can take part in a chemical change. Atoms are the building blocks of molecules but it is possible for one or two atoms of the same kind to be a molecule (of elements). If more than one kind of atom combines to form a molecule, then that molecule is the smallest particle of a compound. It is a mistake to call atoms the smallest particles of elements and molecules the smallest particles of compounds. Refer to the definitions above. A molecule is the smallest particle of *any* pure substance. There are 92 elements that occur in nature. A dozen or so more have been produced in laboratories as a result of nuclear reactions. There are literally millions of compounds from small two-atom molecules to those made up of hundreds of atoms.

### SOLIDS, LIQUIDS AND GASES

Matter can be classified by its *state* at normal temperatures on the surface of earth. Some materials exist as *solid*, some as *liquid* and others as *gas*. Table 1 distinguishes the properties of each. Internal forces give solids their own shape. Internal forces and gravity form the surface of a liquid but the lower boundary will be that of the container. The boundary of a gas is the inner surface of its container. The definite shape of solids allows then to react internally to shearing stresses where liquids and gases cannot. This fact gives liquids and gases their fluid properties. The internal nature of solids, liquids and gases is discussed near the end of this Information Sheet.

| | Shape | Volume |
|---|---|---|
| Solid | Definite | Definite |
| Liquid | Indefinite | Definite |
| Gas | Indefinite | Indefinite |

Table I States of matter

## SUB-ATOMIC PARTICLES

The building blocks of atoms are electrons, protons and neutrons. Table 2 shows the differences between the three particles. The differences in electric charge is probably the most commonly known feature of the three. The most uncommonly known trait is that all three have nearly the same volume. The electron is much lighter than the other two. The proton and neutron have nearly the same mass. One electron charge just cancels one proton charge, making a pair  electrically neutral.

| | Charge | Mass | Volume |
|---|---|---|---|
| Electron | - | 1 | About the same |
| Proton | + | 1836 | |
| Neutron | 0 | 1837 | |

Table II Sub-atomic particles

## PLANETARY MODEL OF THE ATOM

Although photographs of very large molecules have been made by the use of electron microscopes, no one has ever "seen" the sub-atomic particles or even individual atoms. However, a mental picture or model of the atom has been divised that explains their behavior. The following numbered statements describe the basic model. A more refined model is described in a later module.

1. The nucleus or center is made up of protons and neutrons.
2. Nearly all the mass of an atom is in its nucleus.
3. Electrons revolve about the nucleus in definite orbits or shells.
4. An atom is almost entirely empty space.
5. A normal (electrically neutral) atom has the same number of electrons in orbit as there are protons in the nucleus.

Statement 2 follows from statement 1 and 5. All atoms, except hydrogen, have some neutrons as well as protons in the nucleus and there is always one proton for each electron. Hydrogen atoms then must have smaller percentages of mass in the nucleus than any other atom. Hydrogen atoms have only 0.0055% of its mass that is not in the nucleus. Uranium has only 0.021% not in the nucleus. The mass not in the nucleus resides in the electrons.

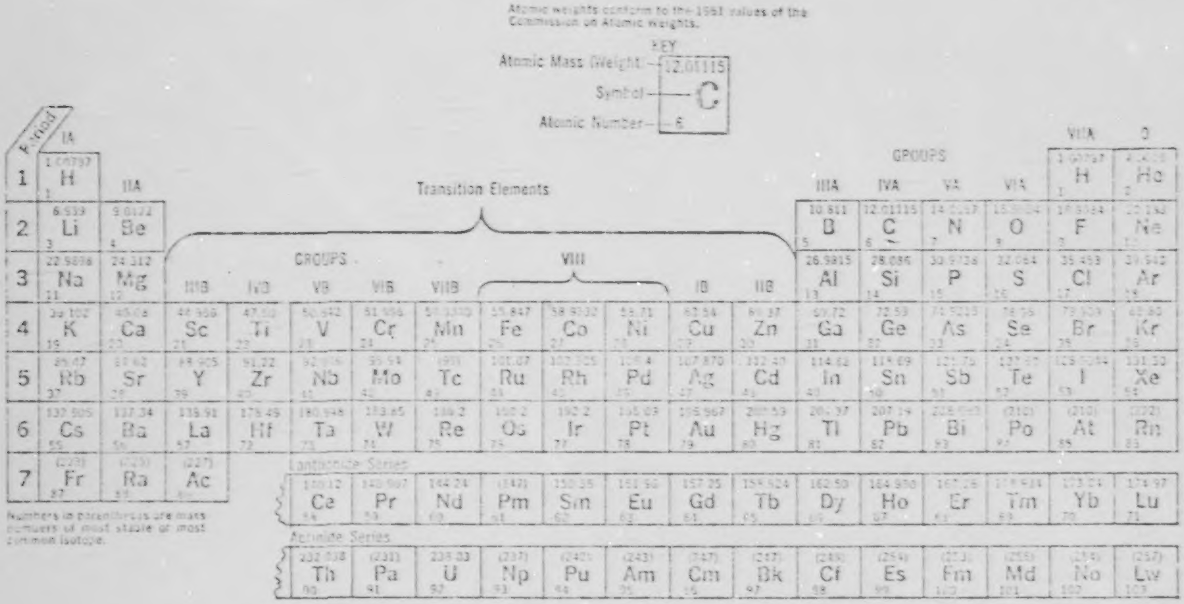
Statement 4 says that most of the space within an atom is empty. The radius of most atoms is about $10^4$ times larger than the nucleus. This means the volume of an atom is about $10^{12}$ times larger than its nucleus. The radius of electrons, protons and neutrons is about $10^{-13}$ cm while most atoms have radii ranging about $10^{-8}$ cm. If an atom were a mile in diameter, the nucleus would range from the size of a marble to the size of a tennis ball depending on the kind of atom.

Statement 3 indicates the planetary aspects of atoms and also indicates an electron must stay in an orbit with a very definite radius. Atoms have only a small number of orbits containing electrons in their ground state. More details are discussed below.

## THE PERIODIC TABLE OF ELEMENTS

The periodic table provides a lot of information about specific atoms and about atoms in general. The chart is divided into a number of small squares, each representing one kind of atom or element. The letters in each square is the chemical symbol of the element. The numbers below the chemical symbol is the atomic number.

The atomic number of an element is the number of protons in the nucleus of atoms of that kind. If the atom should gain or lose a proton or two it becomes an atom of a different element. This would occur only in nuclear reactions. If the atom gains or loses electrons, however, it simply becomes an electrically charged atom (ion) of the same kind. For this reason the kind of atom is determined by the number of protons in the nucleus.



Atomic weights conform to the 1961 values of the Commission on Atomic Weights.

KEY
Atomic Mass (Weight) — 12.01115
Symbol — C
Atomic Number — 6

| Period | IA | IIA | IIIB | IVB | VB | VIB | VIIB | VIII | VIII | VIII | IB | IIB | IIIA | IVA | VA | VIA | VIIA | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | | | | | | | | | | | | | | | | H | He |
| 2 | Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| 3 | Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| 4 | K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| 5 | Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| 6 | Cs | Ba | La | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| 7 | Fr | Ra | Ac | | | | | | | | | | | | | | | |

| Lanthanide Series | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actinide Series | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lw |

Numbers in parentheses are mass numbers of most stable or most common isotope.

Table III Periodic table of the elements (U. S. A. F.).

The number above the chemical symbol is the atomic mass. Since the atomic mass of protons and neutrons is approximately one atomic mass unit (amu), the atomic mass of an atom is approximately equal to the number of protons and neutrons in the nucleus:

> The atomic mass is approximately equal to the atomic number plus the number of neutrons in the nucleus.

To find the approximate number of neutrons in an atom, round off the atomic mass to the nearest whole number and subtract the atomic number.

Example: Find the number of protons and neutrons in the nucleus of iron (Fe) atoms.

Given: (from table) atomic number = 26
atomic mass = about 56

Solution: number of neutrons = 56 - 26 = 30
number of protons = 26

If the atom is not ionized it also has 26 electrons. In a sample of any given element, the atoms do not all have the same number of neutrons. Some iron atoms, for example, have 28 neutrons. Others have 30, some have 31 and some 32. In any sample of iron, the ratio of each kind is fairly constant so the average atomic mass is 55.847.

> Isotopes are atoms with the same atomic number but different atomic masses (different numbers of neutrons).

The electron structure (ground state) of atoms is also described by the periodic chart. Notice the chart is divided into rows (horizontal) and columns (vertical). The row number (period) indicates the number of orbits that any atom in that row has which contains electrons. There are eighteen elements in row 4, for example. In each of these there are four orbits with electrons in them. The 26 electrons in iron atoms are contained in four specific orbits, for example, the orbits are numbered starting with the innermost and working outward, toward the outer orbits.

The number of electrons in each specific orbit can be determined in most cases by a set of simple rules:

Rule 1. The maximum number of electrons (N) in orbit number (n) is given by the formula:

$$N = 2n^2$$

The first orbit can have 2 electrons, the second 8, the third 18, etc.

Rule 2. The maximum number of electrons in the outermost orbit is 8 (2 for orbit number 1).

Rule 3. The actual number of electrons in the outermost orbit is given by the column number (for A columns only). Elements in all other columns (called transition elements) have two electrons in the outer most orbit.

Beginning with atomic number 1 and working gradually to higher and higher atomic numbers the electron structure of each atom can be determined. One electron is added to the outermost orbit with each increase in atomic number up to the maximums indicated in rules 1 and 2. Transition elements have atoms in which electrons are added to an inner orbit. Table 4 indicates the number of electrons in each orbit for the first 38 elements. Column VIIIA of the perioic chart all have eight electrons in their outermost orbit (helium has two). This is a very stable electronic arrangement. These elements are called the inert gases.

| ATOMIC NUMBER | ORBITS<br>1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 | --- | --- | --- | --- |
| 2 | 2 | --- | --- | --- | --- |
| 3 | 2 | 1 | --- | --- | --- |
| 4 | 2 | 2 | --- | --- | --- |
| 5 | 2 | 3 | --- | --- | --- |
| 6 | 2 | 4 | --- | --- | --- |
| 7 | 2 | 5 | --- | --- | --- |
| 8 | 2 | 6 | --- | --- | --- |
| 9 | 2 | 7 | --- | --- | --- |
| 10 | 2 | 8 | --- | --- | --- |
| 11 | 2 | 8 | 1 | --- | --- |
| 12 | 2 | 8 | 2 | --- | --- |
| 13 | 2 | 8 | 3 | --- | --- |
| 14 | 2 | 8 | 4 | --- | --- |
| 15 | 2 | 8 | 5 | --- | --- |
| 16 | 2 | 8 | 6 | --- | --- |
| 17 | 2 | 8 | 7 | --- | --- |
| 18 | 2 | 8 | 8 | --- | --- |
| 19 | 2 | 8 | 8 | 1 | --- |
| 20 | 2 | 8 | 8 | 2 | --- |
| 21 | 2 | 8 | 9 | 2 | --- |
| 22 | 2 | 8 | 10 | 2 | --- |
| 23 | 2 | 8 | 11 | 2 | --- |
| 24 | 2 | 8 | 12 | 2 | --- |
| 25 | 2 | 8 | 13 | 2 | --- |
| 26 | 2 | 8 | 14 | 2 | --- |
| 27 | 2 | 8 | 15 | 2 | --- |
| 28 | 2 | 8 | 16 | 2 | --- |
| 29 | 2 | 8 | 17 | 2 | --- |
| 30 | 2 | 8 | 18 | 2 | --- |
| 31 | 2 | 8 | 18 | 3 | --- |
| 32 | 2 | 8 | 18 | 4 | --- |
| 33 | 2 | 8 | 18 | 5 | --- |
| 34 | 2 | 8 | 18 | 6 | --- |
| 35 | 2 | 8 | 18 | 7 | --- |
| 36 | 2 | 8 | 18 | 8 | --- |
| 37 | 2 | 8 | 18 | 8 | 1 |
| 38 | 2 | 8 | 18 | 8 | 2 |

Table IV Electron structure

Other atoms tend toward a state of having eight electrons in the outer orbit, also. Those in the VIA and VIIA columns lack only one or two electrons so they easily attract any electrons that happen to be passing nearby. Those in columns IA and IIA (and the transition elements) easily shed their one or two electrons. In either case they become electrically charged atoms called ions. An ion is an atom that has gained or lost some of its electrons.

CHEMICAL BONDS

Chlorine atoms (atomic number 17) have seven outer electrons while sodium atoms (atomic number 11) have only 1. If chlorine and sodium atoms are near each other, the chlorine atoms will strip the single outer electron from the sodium atoms. Both kinds of atoms then have eight electrons in their outermost orbits. The sodium atoms are now positively charged ions; the chlorine atoms are negatively charged. Like any other particles with unlike charges, they will attract each other. The force of attraction is relatively large and the two atoms are bonded together (Ionic bonds). Together they form a molecule of sodium chloride (common table salt). The new particle becomes a totally new substance. It has properties all its own and unlike the properties of sodium or chlorine, separately.

Sometimes two or more atoms combine in such a way that they share electrons. Water, for example, is made up of two hydrogen and one oxygen atom. Oxygen has six outer electrons and the two hydrogen atoms each have one. The three atoms share their eight outer electrons.

# ELECTRICAL POLARIZATION

Electrons orbit the atom at a very high speed. The electron in a hydrogen atom travels at $2.2 \times 10^6$ m/s. Its radius is $5.3 \times 10^{-11}$ m, so it makes $6.7 \times 10^{15}$ rev/s. The electron cannot be thought of as a point charge. The charge is spread out over the surface of a sphere surrounding the atom. There will be one smeared out surface for each orbit containing electrons. The surface may have some thickness to it due to elliptical orbits but the greatest charge intensity is at a specific radius. The surface charge intensity is relatively weak compared to the positive charges concentrated in the nucleus.

In molecules of more than one atom, the same thing happens. The two hydrogen atoms and oxygen atom in a water molecule do not line up with their centers along a line. Instead they make an angle of about 105° with the oxygen nucleus at the vertex (see figure 1). Picture this molecule in three dimension: If the oxygen molecule were the size of a basketball, the hydrogen atoms would be about the size of a soft ball. If the space between the three balls were packed with putty and smoothed, it would form a surface similar to the outer electron charge surface of a water molecule. Notice there is an inner surface formed by the two electrons in the oxygen's first orbit. No doubt, the electron surfaces are distorted somewhat by the pull from the three positive points.

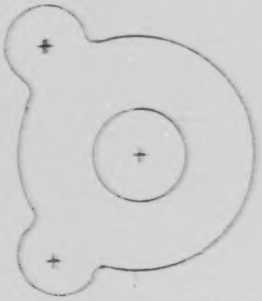


Fig 1 Water molecule

Because of the uneven distribution of the three positive points and the odd shaped electron surface, the molecule is said to be electrically polarized. To illustrate this, imagine a negatively charged rubber rod held close to a pith ball. The electrons in the pith ball are pushed to the opposite side (figure 2a). The pith ball is polarized with a center of positive charge and a center of negative charge. It has positive and negative poles even though it is, overall, a neutral body. There is a greater attractive force on the positive end than there is repulsive force on the negative end since the positive pole is closer to the charged rod. The pith ball swings over and touches the rod (figure 2b) and becomes charged. Electrons are transferred from the rod to the ball. Since it is now a charged object, the pith

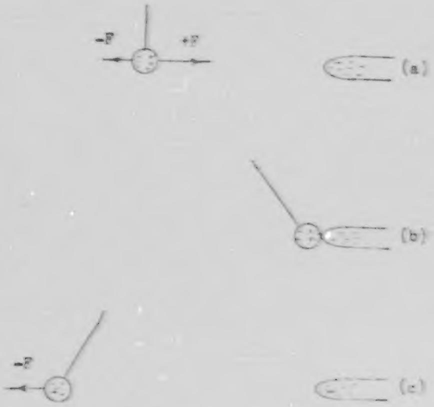


Fig 2 Charging a pith ball

ball is repelled by the charged rod (figure 2c).

The water molecule has electric poles, also. However, it is due mainly to the uneven distribution of the charges within it. One end of the molecule will be more positive than the other. Other molecules are polarized the same way. Single atoms (assumed spherical) will have their electron surfaces distorted when other atoms or molecules approach them. Thus, they become polarized, too.

When two water molecules approach each other the positive end of one will attract the negative end of the other. In this same way, almost any molecule of any kind tends to attract any other molecule. The force of attraction between polarized molecules is considerably less than the force of attraction between ionized atoms, of course. Ions are electrically charged objects. Metallic bonding is another kind of force that holds matter together and is mainly due to the flow of free electrons around large groups of atoms.

## COHESION AND ADHESION

Most molecules are polarized. When molecules of the same kind are near each other they attract each other with a force known as cohesion. If the molecules are not the same kind the attractive force is called adhesion.

Water molecules attract water molecules. Mercury atoms cohere to mercury atoms. Paint molecules attract the molecules of the metal body of an automobile. Glue molecules stick to wood molecules. Dirt sticks to your hands. Ink sticks to paper. Oil sticks to the bearings of an automobile engine. Thin gold foil will adhere to other metals. Mercury will adhere to silver and gold. Solder adheres to copper.

Cohesive and adhesive forces are effective only at a very small distance, however. You have probably seen a broken piece of cast iron. The pieces can be fitted back together so closely that the crack is indistinguishable. The cohesive forces are not strong enough, so the piece falls apart again when you let to of it.

If plates of metal or glass are made smooth enough and fitted together, they stick together by cohesion (gauge blocks, for example). Not only are the molecules close together but a great many of them are in molecular contact. Consider the force necessary to pull the molecules of an unbroken steel rod apart. It takes many tons of force to pull a 1 in rod in two. Molecular forces can be very strong when many molecules act together. The cohesive forces may not be the same in all directions, however. Layers of mica, for example, can easily be peeled off but mica is quite strong in the other two directions.

SURFACE TENSION

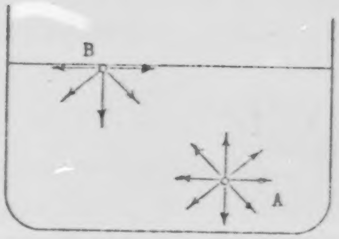


Fig 3 Surface molecules

Do you know why a needle or razor blade will "float" on the surface of water? In figure 3 molecule A has cohesive forces acting on it in all directions. It is being "pulled" in all directions at once. In contrast to this, a surface molecule (B) is not attracted in an upward direction. The forces acting on surface molecules is quite different from those acting on internal molecules. They are so different, in fact, that the surface molecules act like a membrane stretched over the surface, somewhat like the dried surface on an old can of paint. A needle or razor blade will float if they are laid carefully on the surface.

If a floating needle or razor blade is observed closely, the surface appears to be depressed by the weight. If the needle or blade should penetrate the surface it will sink immediately. The surface molecules appear to act like an elastic membrane that stretches around the liquid and pulls the surface inward. This phenomenon is called surface tension. It tends to create a shape to the surface that has the least possible surface area. Free droplets of water take on a spherical shape. For a given volume a sphere has the least surface area. All the following objects have the same volume (1 in$^3$) but different surface areas. A rectangular solid 1 x 100 x 0.01 has a surface area over 200 in$^2$. A rectangular solid 1 x 4 x 0.25 has a surface of 10.5 in$^2$. A cube 1 x 1 x 1 has a surface of 6 in$^2$. A cylinder with a diameter of 1.124 in and height of 1 in has a surface area of 5.54 in$^2$. A sphere of diameter 1.22 in has a surface of 4.81 in$^2$. The surface area of a sphere is the least amount possible for any given volume.

Surface tension is defined as force per unit length:

$$T = F/\ell \qquad 1.$$

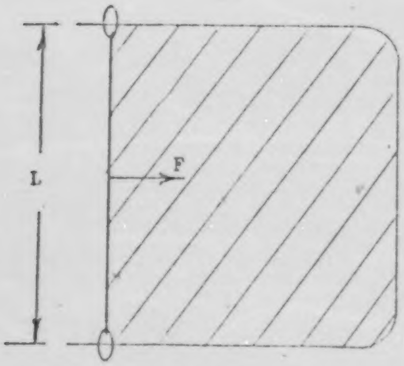


Fig 4 Surface tension

Where $\ell$ is the length of the edge of the surface creating the force. Figure 4 shows a soap film formed in a U-shaped wire. A straight movable wire forms the left edge of the film. Surface tension will pull the straight wire all way to the right, reducing the area of the soap film. In this case the length of the surface edge is twice L since the soap film has a surface on both front and back sides. So the force is given by: F = 2TL

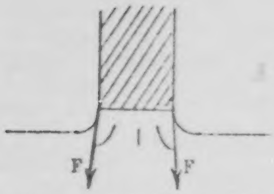


Fig 5 Surface tension

When a rod is pulled out of a liquid the surface of the liquid is distorted as shown in figure 5. The force required to withdraw the rod is $F = \pi dT$ where $\pi d$ is the circumference of the rod. A tube would require more force since another surface would be formed along the internal circumference.

Surface tension creates an internal pressure inside a water droplet. The downward force on the upper hemisphere is $2\pi rT$ where r is the radius. When this force is divided by the cross-sectional area the pressure is found to be:

$$P = \frac{2T}{r} \qquad 2.$$

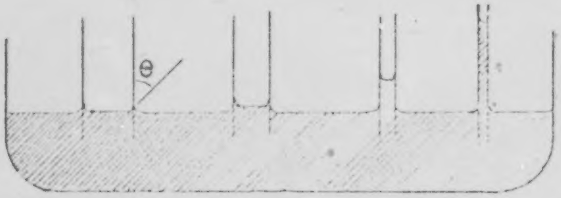
| Substance | Surface tension (N/m) |
|---|---|
| Alcohol | 0.022 |
| Soap solution | 0.026 |
| Glycerin | 0.063 |
| Water | 0.073 |
| Mercury | 0.55 |

Table V Surface tension

This formula also will give the pressure inside an air bubble within a liquid (in excess of the liquid pressure). A soap bubble has an internal and an external surface so the pressure is twice that given by equation 2.

CAPILLARITY

When a glass tube that is open on both ends is placed with one end under a liquid, a process called capillarity takes place. Capillarity is the rise (or fall) of the liquid in fine bore tubes. The liquid molecules are attracted upward by the glass molecules by adhesion. These molecules in turn attract other nearby liquid molecules and pull them upward by the force of surface tension. This process continues until the water is raised to a point where the upward pull of surface tension is balanced by the weight of the liquid in the tube. Capillarity pulls the water higher in smaller bore tubes. The upward force on the column of liquid due to surface tension is $2\pi rT \cos\theta$ where $\theta$ is the angle of contact between liquid and the tube. This force is balanced by the weight of liquid given by the density formula: $W = \pi r^2 hdg$ where h is the height the liquid rises. Therefore:



$$h = \frac{2T \cos\theta}{rdg} \qquad 3.$$

If the liquid wets the tube the angle is 0°. When the liquid doesn't wet the tube the angle is greater than 90° and h will be negative; that is, the liquid is depressed in the tube. Water on paraffin and mercury on glass are two examples of this with the angle being 110° and 140°, respectively.

The wick in a lamp utilizes capillarity to raise fuel to the outside of its container, so it can burn slowly and safely. Sponges, towels and blotters soak up liquids by capillary action. Sawdust will soak up oil on the floor of a garage. Capillarity takes place in living things to transport blood or tree sap. Solder makes a good contact with all the strands of an electrical condutor and would even travel up inside the insulation if it didn't solidify first. Some bearings are porous and absorb oil by capillary action. Large industries have been formed to produce waterproofing agents as well as wetting agents (detergents) to either prevent or aid capillary action.

## CRYSTAL FORMATION

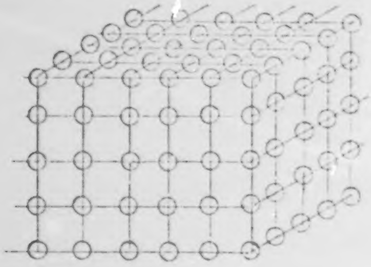


Fig 7

In the liquid state, molecules have some freedom to move around. They move fast enough to escape the cohesive forces. The molecules slow down, however, as the liquid is cooled until they become stuck to each other. The molecules become bound very tightly. When this happens they will align themselves in a uniform way. As one example they may line up as in figure 7 to form a perfect rectangular solid. Others form other solid figures whose sides might be parallelograms or triangles.

Usually the crystals form flat surfaces, possibly many of them. They sometimes will cleave (can be cut) along certain planes, (See figure 8). It is because of the different cleavage planes that one sees crystals whose edges or corners seem to be cut off. Many times they grow this way.

Minerals are naturally occuring substances, many of which are found in crystaline form. Quartz, calcite, feldspars, diamonds, salt, snow, fools gold, etc. are common examples. If one examines rocks closely, she or he will see the mixture of minerals. Rocks are aggregates of minerals.

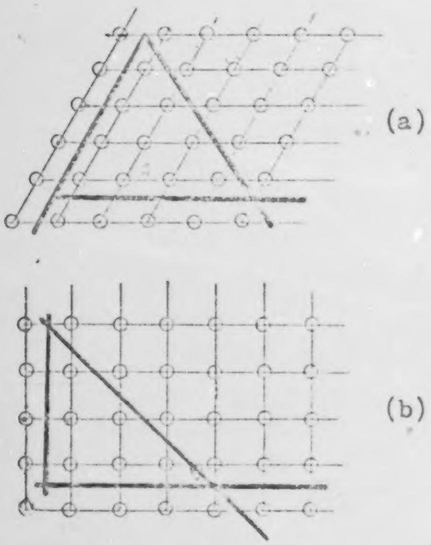


Fig 8

Many substances such as molasses, tar, and glass do not crystalize. They are considered supercooled liquids that have become very rigid. They have more of the properties of liquids than solids. Glass will flow like water but at a rate so slow it takes years to be noticeable.

## BROWNIAN MOTION

Brownian movement was discovered in 1827 by Robert Brown, a British botanist, who observed the irregular but lifelike motion of small particles suspended in liquid. These microscopic particles appear to be continually agitated and make a succession of quick jumps first one way and then another. The path of one such particle is shown in figure 9. These particles are very large compared to the liquid molecules. The same phenomenon may be observed by smoke, dust or spray particles suspended in stagnant air.

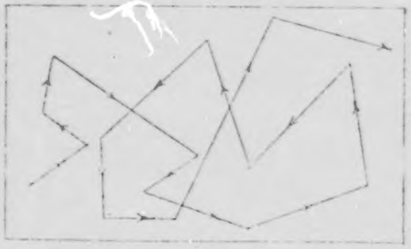


Fig 9

The invisibly small molecules of air or water as the case may be, move at high velocities and bombard the large visible particles from all sides making them dart here and there.

Brownian motion is visual evidence that molecules exist and that they ceaslessly move around. Brownian motion is the basis for a large part of the kinetic and molecular theory described below.

## THE KINETIC AND MOLECULAR THEORY OF GASES

The following nine numbered statements describe the kinetic and molecular theory of gases. Each statement will be explained in further detail.

1. A sample of gas is made up of an extremely large number of molecules.
2. Molecules are very small.
3. The space between molecules of a gas is large compared to the size of the molecule.
4. The cohesive attraction between molecules of a gas is very small (negligible).
5. Molecules are always in motion at high velocities and move in random directions.
6. Molecules of a gas move in straight lines until they collide with each other or with the walls of their container.
7. Collisions between molecules are perfectly elastic.
8. Increasing or decreasing the temperature of a gas increases or decreases the average speed of the molecules. The temperature of the gas is proportional to the average kinetic energy of all the molecules.
9. The internal energy of a gas is the total kinetic energy of all the molecules. The internal energy may be removed in the form of heat.

In the discussion of each statement, the behavior of oxygen molecules ($O_2$) will be used as an example. Statement number 1 refers to numbers. One mole of a substance is a mass in grams of that substance equal to the molecular weight of the substance. For hydrogen ($H_2$), 2 g is required; for oxygen, ($O_2$), 32 g is required; for water ($H_2O$), 18 g is required; table salt (NaCl), 58.4 g is required; etc.

One mole of any substance contains $6.02 \times 10^{23}$ molecules (Avogadro's number). If the substance is a gas at 0°C and normal atmospheric pressure (such as $O_2$), one mole of it will occupy 22.4 ℓ of space (about 6 gal). Even a space of 1 $cm^3$ will have $2.69 \times 10^{19}$ molecules in it. A pin-head sized space (1 $mm^3$) has $2.69 \times 10^{16}$ oxygen molecules in it. Even if the pin-head sized space was pumped out with a vacuum pump to one-thousandth of atmospheric pressure, it would still contain $2.69 \times 10^{13}$ molecules. You can readily see that molecules come in large numbers.

Statements 2 and 3 can be discussed together. If 22.4 ℓ is divided by Avogadro's number, the free space that each molecule has (on the average) to roam around in is determined. This space is $3.72 \times 10^{-20}$ $cm^3$. The size of the oxygen molecules is much smaller than this, though. Its average diameter is $3.2 \times 10^{-8}$ cm. Its volume, therefore, is $1.72 \times 10^{-23}$ $cm^3$. It has a space of about 2160 times its own volume to roam about in. This number can be checked by finding the average density of an oxygen molecule (mass = $5.3 \times 10^{-23}$ g) and dividing by the actual density of oxygen gas ($1.43 \times 10^{-3}$ $g/cm^3$).

The molecules have a space as big as a cube 12.9 times their own diameter to themselves on the average. This cube is $4.14 \times 10^{-7}$ cm on each side. The molecules will travel more distance than this, however, between collisions. The mean free path is $10^{-5}$ cm. Molecules are small and they have a lot of space between them in the gaseous state. Remember, too, that the molecules themselves are mostly empty space.

Statement 4: The cohesive attraction between molecules is all but ineffective at the distance most molecules are apart in the gaseous state. The density of liquid oxygen is 1.14 $g/cm^3$. In the liquid state the molecules are much closer together and have a space of about 3.6 times their own volume to themselves. This indicates that the molecules are confined to a space equal to a cube of about 1.5 times their own diameters. The molecules are much closer together in the liquid and solid states. Unless the molecules are under compression, are very heavy or if the temperature is very low, molecules will be moving fast enough and be far enough away from each other to be unaffected by the presence of other molecules.

Statement 5: Molecules move very rapidly. At 0°C they are moving at an average speed of 461 m/s (1030 mi/h). On the average each one collides $4.6 \times 10^9$ times with other molecules every second after traveling an average distance of $10^5$ cm between collisions. Molecules are so small and there are so many of them that in a given space such as a room there must be as many (at any instant) going north as there are going south, east, west, upward or downward. If this were not so then part of the room would suddenly become evacuated. If there were only 50 or 100 molecules in the room, the probability of all of them ending up in the south half of the room at a given instant would be quite high. In air, the molecules exist in such huge numbers as to make such an event quite impossible. The molecules, therefore, must be moving in random directions.

Statement 6: Molecules have mass. Each mole of oxygen has a mass of 32 g so each molecule has a mass of $5.3 \times 10^{-23}$ g. They have inertia just as any other object does and must obey Newton's first law of motion. Gravity, no doubt, has some effect but they travel such short distances between collisions that its about like a rifle bullet traveling from one end of the room to another. As long as cohesive forces are negligible, they move in straight lines unless acted upon by external forces. This only happens during collisions with other molecules or the container wall.

Statement 7: When a collision is said to be perfectly elastic, the total kinetic energy after the collision is identical to the total kinetic energy just before the collision. A molecule will bounce off a wall with the same energy (and speed) as it had before it hit the wall. When two molecules collide they may exchange their kinetic energy but the sum of the kinetic energies of the two after the collision is the same as the sum before the collision. The average speed of the molecules of air in a tire, for example, will remain the same as long as the temperature doesn't change, (see statement 7). Tires never go flat unless molecules escape. It is the constant pounding of the molecules against the inner walls that create the pressure in a tire.

Statement 8: When the temperature of a gas increases, energy is absorbed by the molecules in the form of kinetic energy. The moving molecules are speeded up when the temperature goes up; they slow down when the gas is cooled. If it is cooled enough, the molecules slow down so much that cohesive forces become effective and the gas changes into a liquid. In the liquid state, they still move around but cannot escape from each other. They are not moving fast enough to overcome the cohesive attractive forces but they are not held in a rigid position.

As they are cooled still farther the molecules slow down even more to a point where the cohesion is strong enough to hold them tight to each other. The liquid changes to a solid. The molecules of a solid are bound tightly together. The molecules no longer move around with respect to each other but simply vibrate back and forth around a locked position. Further cooling takes away more energy and the molecules vibrate less and less violently.

The laws of physics and probability can be used to derive the following equation for the average kinetic energy of the molecules:

$$\overline{E}_k = \tfrac{1}{2}m\overline{v}^2 = 3/2\ kT \qquad 4.$$

Where m is the mass of the molecule $\overline{v}^2$, is the average square of the velocity, T is the absolute temperature (K°) and k is a constant (called Boltzman's constant): $k = 1.38 \times 10^{-23}$ J/k°. The average velocity can be found for any given temperature and it depends only on the mass of the molecule. Oxygen travels at 461 m/s, while hydrogen (1/16 the mass of oxygen) travels at an average speed of 1840 m/s at a temperature of 0°C.

Statement 9: In a gas, the sum total of the kinetic energies of all the molecules is the total internal energy of the gas. There is no other form of energy present as long as electrical attraction can be neglected. This can be calculated by taking the total number of molecules present times the average kinetic energy. The number of molecules is given by the number of moles (n) times Avogadro's number ($N_o$). The average kinetic energy is 3/2 kT.

$$E_t = 3/2\ nN_okT$$

When molecules move slower as the temperature decreases the gas changes into a liquid. The molecules are now held closer together by cohesive attraction. Since forces act on them, it would require work to separate them. A different kind of energy is present. Since the forces can be traced to electrical attraction, the energy can be called electrical energy or attractive energy. Naturally, some kinetic energy is present also. In the solid state the attractive energy is larger than it is in the liquid state.

## DIFFUSION

If a perfume bottle is opened in one corner of a room, the perfume molecules will travel to other parts of the room by a process known as diffusion. Since the perfume molecules are in the gaseous state they move at relatively high speeds according to the kinetic theory. Although they bounce around and collide with other molecules, they will spread since they have independent motion of their own. This results in penetration of every part of the room by the perfume molecules.

If copper sulfate, (blue), or other heavy colored liquid is poured, carefully through a tube to the bottom of a container partially full of water, there will be a fairly sharp line between the water and the heavier copper sulfate. After several days, however, the blue color will have spread upward into the clear water. This is one example of diffusion of a liquid. Diffusion of solids will occur, also, but it takes place very slowly. Several years may be required for it to be noticable at all. Silver and mercury molecules continue to migrate within a tooth filling. The filling becomes stronger with the passage of time but they tend to become more brittle.

## OSMOSIS

If tomatoes, cherries, grapes etc. are placed in water for some time they will burst. If the pores of a membrane, such as the skin of a tomato, are large enough to pass small molecules but not large ones it is called a semipermeable membrane. If a carrot top is cut off and the center bored out, filled with sugar or other substance with large molecules, then plugged by a rubber stopper with a glass tube in it, the process of osmosis may be observed when the carrot is placed in water. The small water molecules penetrate and enter the sugar solution at a much faster rate than the sugar molecules escape from the carrot. The solution in the carrot rises in the glass tube much higher than the water level outside indicating that pressure is present. This pressure is called osmotic pressure. Heavy molecules move slower so they don't enter the pore openings as often as lighter faster molecules.

Secondly, the heavy molecules are bigger and do not find as many openings they can penetrate as the small ones do. Osmosis can be observed in gases through a porous barrier, also.

## GAS PRESSURE

When a baseball strikes a window, a force is exerted on the glass which is probably large enough to break it. When gas molecules hit a surface, there will be many of them in contact with the surface at any instant. Each one exerts a small force. Together they create a steady force. True, they are very small and they have very little mass but remember how fast they travel and how many there are. The atmosphere is a sea of air that exerts forces on everything it touches. Your body has a force of 14.7 lbs on each square inch due to the constant bombardment of tiny molecules. Inside an automobile tire, so many air molecules strike the walls that a pressure of 44.7 lb/in$^2$ is created. Only a space containing a perfect vacuum would have no pressure on its inner walls.

The pressure of a gas can be increased two ways and each way can be accomplished by two methods:

1. Increase the number of molecules per unit volume so more of them will hit each square inch of surface.
    a) Add molecules to the space.
    b) Reduce the size of the space.
2. Increase the speed of the molecules so they strike the surface harder and more often.
    a) Add heat to increase the temperature (and increase molecular speeds).
    b) Do work on the molecules to speed them up (and increase temperature).

Doing the opposite of any of these will, of course, reduce the pressure. An example of 1a would be "pumping" up a tire. The opposite would be letting air out of the tire or evacuating a space with a vacuum pump. An example of 1b would be advancing a piston in a cylinder. The opposite is retracting it.

An example of 2a would be tossing a sealed container into a fire; the opposite is putting it into a deep freeze. When a piston advances in an engine, the molecules bounce off from it at greater speeds than they had just before hitting it. This is similar to hitting a baseball with a bat. The average speed of the molecules increases during compression so the temperature goes up. A retracting piston causes the molecules to bounce off at slower speeds (like bunting a baseball) so the temperature goes down. This is an example of 2b.

Notice that 1b and 2b will occur at the same time. In the cylinder of an engine or air compressor, the molecules are squeezed closer together and are speeded up, both. The compression ratio of modern diesel engines is about 21:1. The molecules are packed 21 times closer together when compressed. This alone would account for a pressure increase to about 300 lb/in$^2$. But, the temperature increases to about 1000°F (538°C). The speed of the molecules increases so that the actual pressure at the end of the compression stroke is 500 $lb/in^2$ instead of only 300 $lb/in^2$. The average speed of the molecules increases by a factor of 1.6 to 1.7.

Some people have the mistaken impression that the temperature of compressed air is higher than that of outside air. This is true at the moment it was compressed, but heat is always transferred from regions of high temperature to regions of low temperature. The temperature of the air in a tire, for example, will fluctuate up and down with the outside air.

## EVAPORATION AND SUBLIMATION

Molecules in a liquid are moving around. They collide with each other transferring their kinetic energy back and forth. Some molecules pick up very high speeds; others move slowly at times. If a high speed molecule is near the surface of the liquid, it may escape from the bonds of cohesion. In some liquids, molecules escape only now and then. In others billions may escape every second. The escape of high speed molecules from the surface of a liquid is a process called evaporation.

Remember, it is the high speed (hot) molecules that escape. Other molecules have to slow down giving up energy to the ones that escape. The high speed escaping molecules leave the remaining molecules at a cooler temperature. Evaporation cools the liquid. The evaporation of perspiration keeps your body cool in the hot summer. Hot soup is cooled by blowing on it. Evaporation rate depends on several things:

1. Surface area of liquid.
2. Winds or air currents blowing over the surface.
3. The pressure of air above the liquid.
4. The temperature of the liquid.
5. The volatility (see textbook) of the liquid.

If water is placed on a wick surrounding the bulb of a thermometer and allowed to cool in front of a fan, the temperature will drop as much as 10°F. If alcohol or gasoline were used, the temperature drop may be as much as 40°F. If freon, propane, anhydrous ammonia or ethyl chloride is used the temperature drop may be more than 100°F and creating temperatures well below freezing. These liquids must be handled with care to avoid frostbite (and other problems).

Sublimation is the same process as evaporation except the molecules escape from solids. The vibrating molecules exchange energy in the same way as they do in liquid. Sublimation is a much slower process than evaporation because of the greater cohesive forces. Snow and ice slowly disappear even when temperatures are below freeezing. Solid carbon dioxide, ($CO_2$) is a substance where the cooling effect is extremely great. It is commonly known as dry ice. Sublimation reduces the temperature to -110°F (-78.5°C). Sublimation also occurs in iodine crystals, moth ball crystals, sulfur and others.

PROBLEMS

## Module P 4 MOLECULAR PROPERTIES OF MATTER

1. An electron has a mass of $9.11 \times 10^{-31}$ kg. Protons and neutrons have masses of about $1.67 \times 10^{-27}$ kg. The mass of an electron is what fraction of the mass of protrons and neutrons? Oxygen is made up of 8 electrons 8 protons and 8 neutrons. What fraction of the mass of oxygen atoms is not in the nucleus?

2. A germanium atom has a radius of about $1.39 \times 10^{-8}$ cm. The radius of its nucleus is about $5.2 \times 10^{-13}$cm. Find the ratio of this atoms radius to the radius of its nucleus. Find the ratio of this atoms volume to the volume of its nucleus.

3. Use the periodic chart only to find the number of protons and neutrons in the nucleus, the number of orbits of electrons, and the number of electrons in each orbit of calcium (Ca) atoms. Of sulfer (S) atoms.

4. A certain TV picture tube has an absolute pressure of one billionth of atmospheric pressure at 0°C. If the internal volume of the tube is 22.4 ℓ, find the number of air molecules it contains. Note: before it was evacuated, it contained $6.02 \times 10^{23}$ molecules. If one billion molecules per second are able to get into the tube from outside through tiny pores, how long will it take for the number of molecules and the pressure to double? Assume the rate of leakage doesn't change.

5. The mass of protons and neutrons is about $1.67 \times 10^{-27}$ kg. The diameter of a germanium nucleus is $1.05 \times 10^{-12}$ cm. If germanium has 73 protons and neutrons, find the density of the nucleus. Note: The densities of all kinds of nuclei are roughly the same. How many tons would 1 teaspoon (3.5 $cm^3$) full of packed protons and neutrons weigh?

6. One end of a 6 in stovepipe is submerged in water. In lifting it out of the water, how much force is required to break the surface tension? (See figure 5 in the Information Sheets).

7. Fog droplets have diameters as small as 0.01 mm. Calculate the pressure inside of one of these smaller droplets due to surface tension. Note: The pull of surface tension on such small droplets is so great that they cannot expand at freezing temperatures. Without expansion they cannot freeze and so exist in the supercooled liquid state at temperatures down to -20°F. Rapid icing occurs on aircraft moving through them.

8. A capillary tube with an inside diameter of 0.1 mm is dipped in water. How high will the water rise in it?

9. A hand pump is set up and the piston is suddenly pushed downward. On the basis of what happens to individual molecules, explain why the temperature of the compressed air increases.

10. If the average speed of the molecules of a gas was doubled, by what factor would the absolute temperature increase? If the temperature of a gas was doubled by what factor would the average speed of the molecules increase?

11. If the temperature of the walls of a container was not the same as the temperature of the enclosed gas, would the molecules bounce off them at the same speed with which they hit? Explain what would happen if the wall was at a higher temperature. At a lower temperature.

12. Exactly what is meant when we say that evaporation is a cooling process? Explain this on the basis of molecular speeds.

13. Why does the pressure of a gas change when the number of molecules per unit volume is changed? Why does the pressure change when the temperature of the gas is changed? Answer both questions in terms of how molecules produce pressure.

14. In the flow of air through a tube, the speed increases at constricted sections (venturi) of the tube. According to the kinetic theory of gases, would you expect the temperature of the air to increase as it passes through the venturi? Try to explain the decrease in pressure within the venturi.

ANSWER KEY (PROBLEMS)

Module P 4 MOLECULAR PROPERTIES OF MATTER

1. 0.00055, 0.00027 or 0.027%
2. 2670, 1.91 x $10^{12}$
3. 20, 20, 4, (2,8,8,2,); 16,16,3,(2,8,6)
4. 6.02 x $10^{17}$, 19.1 years
5. 2.01 x $10^{14}$g/cm$^3$, 776 000 000 ton
6. 0.07 N
7. 14 600 N/m$^2$ or 2.12 lb/in$^2$
8. 14.9 cm
9. See Information Sheet
10. 4, 1.4
11. Molecules of wall vibrate with more (or less) energy than gas molecules. Each contact with the wall brings a transfer of energy from wall molecules to gas molecules.
12. See Information Sheet
13. See Information Sheet
14. Yes, Hint: molecular speeds are greater than flow speeds. Consider glancing blows. Are the molecules farther apart in venturi?

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus Milford, Nebr. 68405

Module: T 2

Title: HEAT AND CHANGE OF STATE

Module Contents:

1. Heat units
2. Heating value of fuels
3. Specific heat
4. Latent heat
5. Change of state

Program: This module was produced especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to study heat as a form of energy. Heat is produced by burning fuel, by doing work against friction and against eleastic flexing and by electrical currents. The efficiency of machines is reduced when energy is lost in the form of heat. This module is prerequisite for the next module on heat transfer.

Producer: Gene Waring

Date Produced: March 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

Module T 2 HEAT AND CHANGE OF STATE

OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define the British thermal unit and the calorie as units of heat energy.
2. Define the mechanical equivalent of heat and state its accepted values in both British and metric units.
3. Define the heating value of
   3 fuels.
4. Define specific heat for solids and liquids. Describe the difference between specific heat at constant volume and at constant pressure for gases.
5. Define heat of fusion and heat of vaporization.
6. State the law of mixtures in terms of the law of conservation of energy and solve problems involving continuous flow calorimeters.
7. Define freezing, melting, boiling and condensation.
8. Describe the processes in objective 7 in terms of the cooling or heating effect they produce.
9. Define freezing point and boiling point and describe the effect of pressure on each. Define cavitation.
10. Solve various problems associated with the formulas and definitions in objectives 2,3,4,5 and 6.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of heat. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key (pink paper) directs you to various learning activities.

Before you take the instructor-graded test ( post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet: Read the information section of the lab instructions. All the textbooks listed below cover most of the objectives of this module. A table of various heat constants is printed on green paper for your convenience. Read your text before reading the information sheets.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 14, pages 352-376 and chapter 16, section 16.1, pages 397-401.

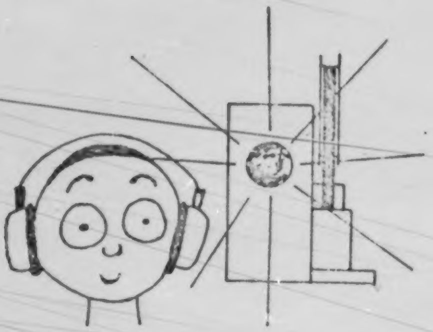
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 15, sections 15.8-15.12, pages 200-206 and chapter 16, pages 210-219.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 16, sections 16.3-16.6, pages 213-219 and chapter 18, pages 236-242.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 14, sections 14.2-14.5, pages 215-228. Also see Information section of the lab instructions.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc. 1st ed., 1966. Read chapter 17, sections 17.2-17.5, pages 263-271.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Conditions Necessary For Combustion (Doubleday Multimedia 13155)
B. Heat is Produced in Different Ways (Doubleday Multimedia 13135)
C. Heat Can Do Work (Doubleday Multimedia 13145)
D. Most Solids Melt (Doubleday Multimedia 13015)
E. Boiling Points of Water (Doubleday Multimedia 13095)
F. Gases Condense as They Cool (Doubleday Multimedia 13065)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving heat problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about the mechanical equivalent of heat. Electrical, electronic and electromechanical students must complete Experiment II, also. Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (T 2) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module T 2 HEAT AND CHANGE OF STATE

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. The British thermal unit is the amount of heat required to raise the temperature of 1 gal of water one degree.

T - F 2. Melting is a cooling process because heat is drawn from the surroundings thereby cooling the surroundings.

T - F 3. When a liquid is boiling, turning up the flame will force the liquid to boil at a higher temperature.

T - F 4. When a substance begins to change state, its temperature will neither rise nor fall until the change is completed.

T - F 5. The mechanical equivalent of heat is kinetic energy.

6. When a vapor condenses into a liquid

a) its temperature rises c) it emits heat

b) its temperature drops d) it absorbs heat

7. The specific heat of aluminum is 0.22 Btu/lb F°. How much heat in British thermal units is required to raise the temperature of a 100 lb casting from 70°F to 1220°F?

a) 253 c) 1150

b) 25 300 d) 115 000

8. The latent heat of fusion of copper is 43 kcal/kg. Express this in British thermal units per pound.

a) 77.4 c) 170

b) 94.8 d) 1.80

9. How much heat is required to raise the temperature of 6 gal of water (50 lb) from 70°F to 212°F and then boil away 10% (5 lb)? The specific heat of water is 1 Btu/lb F° and the latent heat of vaporization is 970 Btu/lb.

10. Water has a specific heat of 1 Btu/lb F°. How many cubic feet of natural gas is necessary to raise the temperature of 250 lb of water (30 gal water heater) from 40°F to 160°F? The fuel value of natural gas is 1100 Btu/ft$^3$. Assume the water absorbs all the heat from the flame.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module T 2 HEAT AND CHANGE OF STATE

| Question - Answer | | If you missed this question, you are directed to these learning activities |
|---|---|---|
| 1. | F | I Reading |
| 2. | T | I Reading |
| 3. | F | I Reading or II Listening/Viewing |
| 4. | T | I Reading |
| 5. | F | I Reading and V Lab Experiment |
| 6. | c | I Reading or II Listening/Viewing |
| 7. | b | III Solving Problems |
| 8. | a | III Solving Problems |
| 9. | 11 950 Btu | III Solving Problems |
| 10. | 27.3 $ft^3$ | III Solving Problems |

320

Table 1 Heating values of various fuels

| Fuel | Btu/lb | Btu/gal | Btu/ft³ | kcal/kg | kcal/ℓ |
|---|---|---|---|---|---|
| Coal* | 13 000 | | | 7200 | |
| Wood* | 6000-8000 | | | 3300-4400 | |
| Diesel fuel | 192 000 | 145 000 | | 10 700 | 9600 |
| Kerosene | 19 800 | 135 000 | | 11 000 | 9000 |
| Gasoline | 20 500 | 115 000 | | 11 400 | 7650 |
| Acetylene | 19 800 | | 1450** | 11 000 | 12.9** |
| Hydrogen | 57 900 | | 325** | 32 200 | 2.9** |
| Natural gas* | 14 100 | | 1200** | 7800 | 10.7** |
| Propane | 19 100 | | 2400** | 10 600 | 21.4** |

* varies - values given are typical or average

** volume at 0°C and 1 atm pressure

Table 2 Heat properties of various materials

| Material | Specific heat | Heat of fusion (kcal/kg) | Heat of vaporization (kcal/kg) | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|---|---|
| Air | 0.240 (Cp)<br>0.171 (Cv) | | 51 | -353 | -315 |
| Alcohol (ethyl) | 0.58 | 25 | 205 | -115 | 80 |
| Aluminum | 0.22 | 77 | | 660 | 2060 |
| Brass | 0.092 | | | | |
| Copper | 0.093 | 43 | | 1080 | 2300 |
| Gasoline | | | 75 | | 80 |
| Ice | 0.50 | 80 | | 0 | |
| Iron & Steel | 0.11 | 30 | | 1500 | 2980 |
| Lead | 0.030 | 6 | 175 | 330 | 1620 |
| Mercury | 0.033 | 3 | 70 | -40 | 360 |
| Steam | 0.48 | | 540 | | 100 |
| Stone | 0.19 (av) | | | | |
| Water | 1.00 | 80 | 540 | 0 | 100 |

Table 3 Boiling point of water at various applied pressures

| Absolute pressure ($lb/in^2$) | Boiling point (°C) (water) | Boiling point (°C) (50% ethylene glycol) |
|---|---|---|
| 0.089 | 0 | |
| 0.18 | 10 | |
| 0.34 | 20 | |
| 1.0 | 38.9 | |
| 1.8 | 50 | |
| 2.9 | 60 | |
| 4.5 | 70 | |
| 6.7 | 80 | 87 |
| 10.2 | 90 | 97 |
| 14.7 | 100 (normal) | 107 |
| 20.8 | 110 | 117 |
| 25 | 116 | 123 |
| 39.3 | 130 | 137 |
| 50 | 138 | 145 |
| 69.2 | 150 | |
| 75 | 153 | |
| 89.2 | 150 | |
| 100 | 164 | |
| 200 | 194 | |
| 300 | 214 | |
| 400 | 229 | |
| 500 | 242 | |

Table 4 Freezing point of water at various applied pressures

| Absolute pressure (atmosphere) | Freezing point (°C) |
|---|---|
| 0 | 0 |
| 400 | -3 |
| 600 | -5 |
| 1100 | -10 |
| 1750 | -15 |
| 2150 | -20 |

Table 5 Calorie values of various foods

| Food | Energy (Cal)* | Food | Energy (Cal)* |
|---|---|---|---|
| milk (1 cup) | 90 | hamburger (3 oz) | 245 |
| carbonated beverage (8 oz) | 70 | steak (3 oz) | 400 |
| beer (8 oz) | 115 | frankfurter (1) | 160 |
| bread (1 slice) | 60 | bacon (2 slices) | 100 |
| butter (1.5 tsp) | 50 | ham (3 oz baked) | 250 |
| American cheese (1 slice) | 110 | fish stick (1) | 150 |
| egg (fried) | 110 | string beans (1/2 cup) | 20 |
| apple pie 1/6 | 400 | baked beans (1/2 cup) | 120 |
| apple | 90 | corn (1 ear) | 80 |
| banana | 130 | celery (1 stalk) | 10 |
| peach | 40 | tomato (small) | 60 |
| peanuts (1/2 oz) | 90 | | |

* Food calories are equal to kilocalories and usually written with a capital C.

Table 6 Calorie expenditures for various activities

| Activity | Calories per hour* |
|---|---|
| Sitting at rest | 15 |
| Standing relaxed | 20 |
| Dressing-undressing | 33 |
| Walking | 130-200 |
| Cycling | 180-300 |
| Swimming | 200-700 |
| Running | 500-930 |

* Rates listed are for average 128 lb woman or 154 lb man.

CAVITATION: Whenever a liquid evaporates, the vapors create pressure above the liquid. This pressure is called the vapor pressure of the liquid and it depends on the temperature. If the temperature is such that the vapor pressure is equal to the applied pressure then the liquid boils. See table 3. This table gives the applied pressure on water and the corresponding boiling point. The table also gives the vapor pressure of water at given temperatures.

Example: What is the boiling point of water used as a coolant in an automobile if the pressure cap provides relief at 25 $lb/in^2$ absolute.

Solution: Table 3 gives a boiling point of 116°C (240°F). Note: Antifreeze solutions would have a different boiling point for the same pressure.

Example: What is the vapor pressure of water at 50°C (122°F)?

Solution: Table 3 gives a vapor pressure of 1.8 $lb/in^2$.

If the temperature of water is 50°C, the water would boil if the applied pressure drops to 1.8 $lb/in^2$. Water will suddenly flash into a vapor even below the surface forming vapor bubbles. The bubbles form continuously and rise to the surface. This process is known as boiling.

In a moving liquid, pressure may drop suddenly. The drop in pressure may be due to the venturi effect or the internal swirls and eddies produced in turbulant flow. The pressure is much lower at the center of such swirls. This usually occurs on the inlet side of a pump or turbine near the blades or propellers. It also occurs in needle valves and jet nozzles.

The sudden vaporization of liquid in such situations is called cavitation and it occurs when the pressure drops below the vapor pressure of the liquid which depends primarily on the temperature. Such cavities do little harm except when they collapse near metal surfaces. They usually collapse downstream from when they were formed in regions of higher pressure.

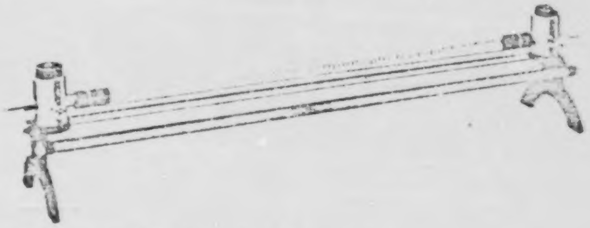
During collapse there is a sudden, momentary very high pressure on the metal impeller blades,jets, turbine blades, etc. The effect may cause mild to severe pitting of the metal on the back of the turbine blade or jet opening. Extreme cavitation occurs when it spreads over large areas and causes instability, vibration, noise and very rapid wear of the metal parts.

## HEATING A GAS

The formula $Q = mc\Delta T$ gives the heat (Q) required to change the temperature ($\Delta T$) of a certain mass (m) where c is the specific heat used for solids, liquids and gases. Gases, however, can be thermally changed by several processes. (See module T 1). The formula is not applicable to isothermal, adiabatic and throttling processes. There is no temperature change in isothermal processes and no heat is added in the other two.

In an isochoric process (constant volume) the heat added goes entirely to raising the temperature of the gas. In an isobaric process (constant pressure), some of the heat increases the temperature while some of it does work on the gas as it changes volume. More heat is required to raise a certain mass of gas through a given temperature range when the process is isobaric than if the process were isochoric. The specific heat at constant volume ($C_V$) of air is 0.171 Btu/lb F°, for example, while the specific heat at constant pressure ($C_p$, is 0.240 Btu/lb F°. Air inside a TV set or radio is heated isobaricly while air in a sealed container is heated isochoricly, for example.

## CONTINUOUS FLOW CALORIMETERS



Continuous flow calorimeter
By permission: The Sargent-Welch Scientific Co.

The device shown in the diagram is a continuous flow calorimeter. The source of heat is a resistance wire enclosed in a glass tube and connected to insulated binding posts. Water or other liquid coolant flows through the tube, continuously, through the inlet and outlet tubes. An outer glass tube provides a dead air space to eliminate heat loss. Thermometers measure the temperature of the flowing water at the inlet and outlet tubes.

The inlet is connected to a constant level tank to provide constant rate of flow of coolant. Once temperature equilibrium is established, the rate of flow (R) can be determined by collecting a volume (V) of coolant over a measured period of time (t). The total heat energy absorbed by the coolant is given by the formula.

$$Q = dVc\Delta T \qquad 1$$

Where d is the density and the product (dV) is the mass of coolant collected. The rate of heat absorbtion (P)(power) by the coolant is Q/t:

$$Q = dRc\Delta T \qquad 2$$

Where P will have units of Btu/s, cal/s, etc. These units can easily be converted to ft lb/s, watts, horsepower etc. The power provided by the flow of electric current is equal to the rate at which heat is absorbed by the coolant.

Example: In the calorimeter described above, 2 ℓ of water is collected in 1.75 min. The inlet temperature is 10°C and the outlet temperature is 15°C. The density of water is 1 kg/ℓ and the specific heat is 1 kcal/kg C°. Find the rate of heat absorbtion in kcal/s and the electric power in watts.

Given:

$V = 2\ \ell$
$t = 1.75\ \text{min} = 105\ \text{s}$
$T_1 = 10^\circ\text{C}$
$T_2 = 15^\circ\text{C}$
$d = 1\ \text{kg}/\ell$
$c = 1\ \text{kcal/kg C}^\circ$

Solution:

$R = V/t = 2\ell\ /105\ \text{s} = 0.019\ \ell/\text{s}$
$P = dRc\Delta t$
$= (1\ \text{kg}/\ell)(0.019\ \ell/\text{s})(1\text{kcal/kg C}^\circ)(5\ \text{C}^\circ)$
$= 0.0952\ \text{kcal/s}$ (Rate of heat absorbed)
$P = (0.0952\ \text{kcal/s})(4186\ \text{J/kcal})$
$= 399\ \text{W}$ (electric power supplied)

Energy gain or power gain can be determined in any device in which fluids absorb heat if the rate of flow and inlet and outlet temperatures are known. An example is the energy absorbed by water flowing through a water turbine dynamometer. Energy loss or power loss can be determined in the same way in devices that have a cooler outlet temperature than inlet temperature. The radiator on a car is an example.

PROBLEMS

## Module T 2 HEAT AND CHANGE OF STATE

1. The units of specific heat are: Btu/lb F°, cal/g C° and kcal/kg C°. Why are the numerical values of the specific heat for a given substance identical?

2. Why does steam at 100°C produce a much worse burn than water at 100°C?

3. Under what circumstances can heat be added to a substance without changing the temperature?

4. What does the word regelation mean? How is it involved in the packing of a snowball?

5. What does the word cavitation mean? Exactly how does cavitation cause metals to wear?

6. A pot of water is boiling on the stove. If you turned the flame up will the water boil at a higher temperature? Explain.

7. When a vacuum is produced over a beaker of water in a bell jar, the water boils. After several minutes the water stops boiling. Why? What has happened to the temperature of the water? Where does the heat of vaporization required by the boiling process come from in this case?

8. Salt is sprinkled on some 32°F ice in a beaker. In a few minutes some of the ice has melted. The temperature of the ice-water brine in the bottom is about 18°F. The temperature of the ice above the brine is about -4°F. Where does the heat of fusion required to melt the ice come from?

9. If there were about 11.5 lb of ice in the beaker in problem 8 and 1.5 lb melts, what must be the resulting temperature of the ice that remains unmelted? Assume all the heat required to melt the 1.5 lb came from the remaining 10 lb of ice.

10. If the specific heat of the human body is 0.9 kcal/kg C°, how many kilograms of water would have to evaporate from a 55 kg woman to lower her temperature by 1 C°? From a 75 kg man? The latent heat of vaporization at body temperature is 580 kcal/kg.

11. If the man and woman in problem 10 each consumed 1600 kcal of food in one day, how much would their temperature rise if all the food energy were converted to heat? Assume no heat is lost by any method.

12. About how many hours could a person walk using only the food energy supplied by one fried egg, one slice of buttered bread and one cup of milk? Assume none of the energy is converted to heat. See tables 5 and 6 in the Information Sheets.

13. How many kilocalories must be added to a 20 kg piece of steel to raise its temperature from 20°C to 100°C?

14. How many kilocalories must be added to a 10 kg piece of aluminum to raise its temperature from 20°C to 660°C?

15. Refer to table 1 in the Information Sheets. Acetylene has a higher heating value than propane when measured in Btu/lb. The situation is reversed, however, when it is measured in Btu/ft$^3$. Explain why.

16. If all 250 ft$^3$ of acetylene in a tank could be burned, how many Btu of heat would be developed? How many kilocalories is this?

17. A 15 kg steel casting at 800°C is quenched in an 8 kg steel container of water at 22°C. If the final temperature of the system is 65°C, how much water was used? Assume no heat losses.

18. A 5 kg brass bushing is placed in a heat-treating furnace and heated to furnace temperature. The bushing is then removed and quickly dropped into a 5 kg steel container with 15 kg of water at 27°C in it. The final temperature of the whole system is 50 C°. What was the furnace temperature? Assume no heat losses.

19. How much heat is produced by a large drill bit used to drill a hole in cast iron if it takes 8 min and 0.5 hp is delivered to the drill bit?

20. Is cavitation a problem on the input side of hydraulic pumps? Under what conditions do vapor bubbles form? Why does pitting occur when the bubbles collapse? On which side of the pump impeller are the vapor bubbles formed and on which side do they collapse.

21. A deep cut is made on the workpiece on a lathe. Cutting oil is used as a coolant which flows at a rate of 450 mℓ/ min. The temperature of the oil flowing onto the workpiece is 24°C and 38.5°C when it runs off. If the specific heat and density of the oil are 0.43 kcal/kg C° and 890 kg/m$^3$, respectively, find the rate at which heat is absorbed by the oil in kilocalories per minute and in watts.

22. The cutting tool on the lathe of the previous problem removes a chip of 2.75 g each second. If the chip's temperature is 90°C while that of the workpiece is 25°C, find the rate at which heat is carried away from the cutting tool by the chip in kilocalories per minute and in watts. The workpiece is steel with a specific heat of 0.11 kcal/kg C°.

23. Combine the answers to problems 21 and 22. If this amounts to 80% of the heat produced, what power is delivered by the lathe to the cutting tool? NOTE: Additional heat is conducted into the work piece and the cutting tool. Some is carried away by the convection of hot oil vapors produced at the site of cutting. Express your answer in watts and horsepower.

24. The cutting tool of the previous problem is doing work at a rate of 320 J each second. It completes one revolution each second (60 rpm). If the cut is being made at a distance of 3 cm from the axis of rotation, find the force the cutting tool applies to the workpiece in newtons. How many pounds is this?

ANSWER KEY (PROBLEMS)

Module T 2 HEAT AND CHANGE OF STATE

1. See definition of heat units and specific heat.

2. Heat is transferred at the boiling point (latent heat of vaporization).

3. Any isothermal process or during change of state.

4. Drop in freezing point due to high pressure.

5. See Information Sheet.

6. No, it just boils faster.

7. Temperature has dropped to the boiling point. Decreases. It must come from the kinetic energy of the molecules since no heat is being added so the temperature drops.

8. See problem 7.

9. -11.2°F (Since some heat came from the melted ice, the temperature is not quite this low).

10. 91.7 g, 125 g

11. 32.3°C , 23.7°C

12. 1.6-2.4 hr

13. 176 kcal

14. 1410 Btu

15. Density of propane is 0.1254 lb/ft$^3$. For acetylene it is 0.07323 lb/ft$^3$.

16. 363 000 Btu. 91 300 kcal.

17. 27.3 kg

18. 728°C

19. 170 Btu

20. Yes, see Information Sheets.

21. 2.5 kcal/min, 174 W

22. 1.18 kcal/min, 82.3 W

23. 320 W, 0.43 hp

24. 1700 N, 382 lb

## EXPERIMENTS

## Module T 2 HEAT AND CHANGE OF STATE

**PURPOSE:** The purpose of this experiment is to study the mechanical equivalents of heat. Work is done against friction causing heat to form in a copper drum. Both the work done and the heat produced is measured and compared.

**CAUTIONS:**
1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horse play is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

## EXPERIMENT I: MECHANICAL EQUIVALENT OF HEAT

**EQUIPMENT:** Check to see if all the following equipment is available before you start. If you have any question, ask the instructor.

1. Base with handle (Ealing 21-2456)
2. Copper block calorimeter
3. Weight and hangar (about 10 kg)
4. Cord with attached slide, S hook and rubber band
5. Thermometer and guard
6. Red plastic cap
7. Vernier caliper

**INFORMATION:** In 1843, James Prescott Joule performed a famous experiment which showed that work and heat were equivalent. He used a calorimeter with an internal paddle wheel which could be turned by the pull of a falling weight. The work done by the falling weight which churned the water in the calorimeter. The temperature of the water was raised as a result of the churning. He calculated the amount of heat produced from the known amount of mechanical work.

The ratio of the mechanical work done ($W_K$) to the amount of heat produced (Q) is called the mechanical equivalent of heat (J) (or Joule's constant).

$$J = \frac{W_K}{Q}$$

The value of J is 778 ft lb/Btu or 4186 J/kcal in the British and MKS measuring systems, respectively.

Heat is always produced when work is done against friction or when work is done while bending, twisting, compression or stretching a material. Tires get warm from flexing; wire gets hot when bent back and forth; rails get warm when a train passes over them; a nail gets warm when pounded with a hammer; bushings get warm from the friction; automatic transmission oil gets very hot from the constant turbulance.

Whenever energy is transmitted from one part of a machine to another, some of it is converted to heat. The heat causes a rise in temperature of the material. The heat energy is then transferred away from the machine and lost. The work output of a machine can never be as great as the input.

In this experiment, all the work is done against friction. The amount of work done and the heat produced are measured and compared. A preliminary experiment is performed to note the temperature rise. The apparatus is then cooled below room temperature so it will absorb heat from the room half of the time. As the temperature of the apparatus rises above room temperature it then gives off heat to the room. The two effects cancel giving good results for the mechanical equivalent of heat.

PROCEDURE:

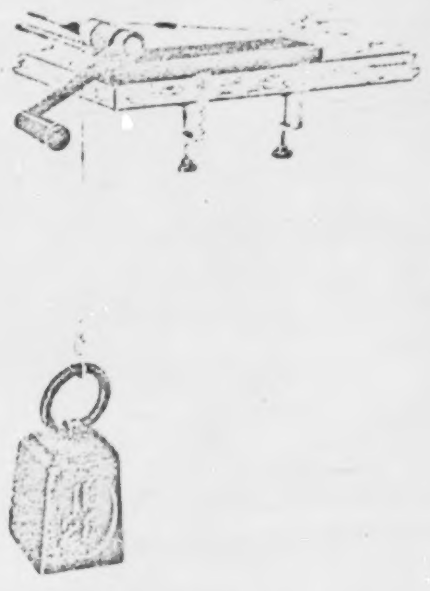
CAUTION: Do not install the thermometer until step 8. Use extreme care with it because no other thermometer will fit the apparatus.

1. Clamp the base (with handle) to the edge of a sturdy table or bench as shown in the accompanying diagram so the load can hang freely.

2. Unscrew the copper drum and measure its diameter and mass. Record these values on the data sheet. DO NOT HANDLE THE DRUM ANY MORE THAN NECESSARY. IT ABSORBS HEAT FROM YOUR HAND.

3. Wind the nylon cord to the copper drum. Start from the handle end and wind five or six turns without overlapping. Wind clockwise as viewed from the handle.
   NOTE: The loop end of the cord with the slider attached should hang down near the weight. The end of the cord with the attached rubber band should run over the top

4. Attach the S hook to the weight hanger and the rubber band to the anchor-pin on the back of the base. You may need to turn the handle to make both connections.



Mechanical equivalent of heat apparatus
By permission: The Ealing Corporation.

5. Rotate the handle to lift the weight. The weight should lift completely off the floor and there should be little or no tension in the rubber band. Make adjustments as necessary. Don't rotate the handle more than necessary.

6. Check to see if the cord "travels" to one end of the drum. If it does, the apparatus is not level. Make adjustments by placing cardboard shims under the low side.

7. Insert the U-shaped thermometer guard in the two holes in the base under the copper drum.

8. Slide the red plastic sleeve on the thermometer. Place a drop of glycerin on the thermometer bulb for good thermal contact and attach the thermometer to the copper drum with the sleeve. Push the thermometer in until it touches the bottom of the hole. HANDLE THE THERMOMETER WITH CARE.

9. Record the temperature. It should be near room temperature.

10. Rotate the handle 100 turns. Do this quickly enough to finish in about one minute.

11. When the temperature of the drum stops rising, record the temperature and the rise in temperature.

12. Disassemble the apparatus and cool the drum to a temperature equal to one-half the temperature rise below room temperature. Record the temperature.

NOTE: Cooling can be accomplished by running cold water over the drum. The temperature may go below that required but by the time you dry the drum and reassemble the apparatus it should be near the correct temperature. Warm it with your hands if necessary. THE DRUM MUST BE DRY BEFORE RE-ASSEMBLING.

13. Turn the handle exactly 100 turns. Try to complete the 100 turns in about one minute.

14. As soon as the 100 turns are completed, lower the weights to the floor without further slipping of the cords against the drum.

15. Carefully observe the temperature and record the highest temperature reached by the drum.

16. Record the weight. Include the weight of the hangar and the holding clip. Most of the weights are marked. The total weight is the frictional force acting on the copper drum.

17. Calculate the work done against friction. The distance traveled is: 100 turns times the circumference.

18. Calculate the heat produced ($mc\Delta T$). The specific heat of copper is 0.093 kcal/kg C°.

19. Calculate the mechanical equivalent of heat.

20. Compare your calculated value with the accepted value by finding the percentage error. Discuss the principal sources of error.

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus
Milford, Nebr. 68405

Module: T 1

Title: TEMPERATURE AND THERMAL EXPANSION

Module Contents:
1. Temperature
2. Linear expansion (solids)
3. Volume expansion (solids, liquids and gases)

Program: This module was written especially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics

Purpose: The purpose of this module is to study temperature and some of the effects on matter when temperature is changed. The temperature of an object is the property that controls the flow of heat energy and the size of the object. Both the transfer of heat and thermal expansion are important in manufacturing industries. Especially, in the tools used in industry and the manufactured product. This module is a prerequisite for the modules that follow.

Produced by: Gene Waring

Date Produced: February 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

## STUDENT INSTRUCTIONS

## Module T 1 TEMPERATURE AND THERMAL EXPANSION

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Define thermal equilibrium and temperature.

2. Describe the Fahrenheit, Rankine, Celsius and Kelvin temperature scales and convert a given temperature from one to the other. Describe absolute and "gauge" scales.
3. State the formula for linear thermal expansion for solids and use the formula to solve various problems.
4. Define differential expansion and describe the expansion of bimetalic strips.
5. State the formulas for volume expansion for solids and liquids and solve various problems with it.
6. Describe the unusual expansion of water.
7. State the general gas law.
8. Define each of the following gas expansion processes: isothermal, isobaric, isochoric, adiabatic and the throttling process.
9. Solve various problems involving the expansion processes (objective 8) using the general gas law.
10. State the formula for resistance of a wire in terms of length cross-sectional area and resistivity and solve various problems with it. This objective is for electrical, electronics and electromechanical students only.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of thermal expansion. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

## LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in the textbooks. Information about special applications may also, be presented in the problem set printed on ivory paper.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read chapter 13, pages 321-349.

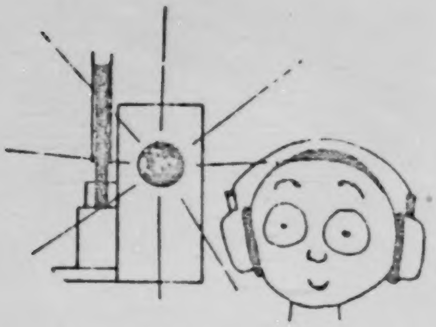
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read chapter 14, sections 14.4-14.5, pages 183-185 and chapter 15, sections 15.1-15.7, pages 195-200.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden. L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 16, sections 16.1-16.2, pages 208-212 and chapter 17, pages 220-228 and chapter 18, pages 229-234.

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 14, section 1, pages 213-214, and chapter 15, sections 15.1-15.5 pages 235-250.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 17, section 17.1, pages 260-262 and chapter 18, sections 18.1-18.5, pages 274-282.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Heat Expands Metals (Doubleday Multimedia 13035).
B. Heat Expands Liquids (Doubleday Multimedia 13045).
C. Heat Expands Gases (Doubleday Multimedia 13055).
D. Gas Pressure and Temperature (Doubleday Multimedia 13245).
E. Heat Affects the Pressure of Gases (Doubleday Multimedia 13085).
F. Properties of a Gas (BFA-Ealing 80-296).

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving thermal expansion problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is one experiment in this module. It will give you practice in learning about thermal expansion.
Read the laboratory instructions in this booklet (on yellow paper, and pay particular attention to the cautions given). Obtain a laboratory data sheet (T 1) and the equipment from the instructor. Keep this booklet open to the instruction pages and proceed step by step with the experiment.

VI. Report: If you are an automotive or diesel student, complete the report on thermal expansion of a piston if your instructor requires it. Instructions are printed on salmon (orange) paper.

## TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.).

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

Module T 1 TEMPERATURE AND THERMAL EXPANSION

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. Thermal equilibrium exists between two bodies when they contain the same amount of heat.

T - F 2. An isothermal expansion process is one in which temperature doesn't change.

T - F 3. Absolute zero may be thought of as the temperature at which distilled water freezes.

T - F 4. When a metal plate with a hole in it is heated, the diameter of the hole increases.

T - F 5. The density of most materials increases as the temperature increases.

Match the following (6,7 and 8):

| | | |
|---|---|---|
| ______ 6. | Bathing suit | a) 308 K |
| ______ 7. | Sweater | b) 10°C |
| ______ 8. | Thermal underwear | c) 450°R |

9. The temperature of an empty steel tank of 1000 gal capacity goes up in the hot sun by 80 C°. The coefficient of linear expansion for steel is $11 \times 10^{-6}$/C°. By how many gallons does the volume of the tank increase.

a) 2.64 gal c) 1.58 gal

b) 0.88 gal d) 0.11 gal

10. An oxygen tank has a volume of 2 $\text{ft}^3$ and a gauge pressure of 2200 $\text{lb/in}^2$. How many cubic feet of space would the oxygen occupy at atmospheric pressure (14.7 $\text{lb/in}^2$)? Assume an isothermal expansion.

ANSWER KEY TO THE SELF-EVALUATION TEST

Module T 1 TEMPERATURE AND THERMAL EXPANSION

| Question-Answer | | If you missed this question, you are directed to these learning activities |
|---|---|---|
| 1. | F | I Reading |
| 2. | T | I Reading or III Solving Problems |
| 3. | F | I Reading |
| 4. | T | I Reading |
| 5. | F | I Reading or III Solving Problems |
| 6. | a | III Solving Problems |
| 7. | c | III Solving Problems |
| 8. | b | III Solving Problems |
| 9. | a | III Solving Problems or V Lab Experiment |
| 10. | 301 $ft^3$ | III Solving Problems |

INFORMATION SHEET

Module T 1 TEMPERATURE AND THERMAL EXPANSION

Thermometers are devices which have internal properties that change when the temperature changes. Solids, liquids and gases expand, electrical resistance changes, voltage across a thermocouple changes, colors change and other changes occur when temperature is changed. All of these properties are used in various types of thermometers.

When a thermometer is used (such as a mercury type), heat is exchanged between the material being tested and the thermometer until the temperature becomes constant. When this state is achieved, the thermometer and the substance are said to be in thermal equilibrium. Heat is no longer exchanged between the two objects and their temperatures are equal. When two objects are both in thermal equilibrium with a third object, they are in thermal equilibrium with each other.

Temperature is measured in Fahrenheit and Celsius degrees. These are the so-called gauge temperature scales since the zero is not at the bottom of the scale (similar to gauge pressure scales). The absolute pressure scales have zeros at the bottom of the scale and so do absolute temperature scales. The Kelvin scale has the same sized units as the Celsius scale. Rankine and Fahrenheit scales have the same sized units. Notice that between the freezing point and boiling point of water (see table 1) there are 180 degrees on the Fahrenheit and Rankine scales while on the Kelvin and Celsius, there are 100 degrees. This gives rise to the following conversion formulas:

|  | Gauge |  | Absolute |  |
|---|---|---|---|---|
|  | °F | °C | K | °R |
| Boiling point ($H_2O$) | 212 | 100 | 373 | 672 |
| Body temperature | 98.6 | 37 |  | [illegible] |
| Room temperature | 68 | 20 |  |  |
| Freezing point ($H_2O$) | 32 | 0 | 273 | 460 |
| Absolute zero | -460 | -273 | 0 | 0 |

Table 1. Temperature scales

$$\frac{F - 32}{9} = \frac{C}{5} \qquad 1$$

$$\frac{R}{9} = \frac{K}{5} \qquad 2$$

$$R = F + 460 \qquad 3$$

$$K = C + 273 \qquad 4$$

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The ratio of 180/100 reduces to 9/5 in equations 1 and 2. Whenever a change in a quantity occurs due to a change in temperature then it is permissible to use "gauge" temperatures for solving problems. However, if a quantity depends on the actual temperature the absolute scales must be used. Note that the degree is not used with the Kelvin scale: 30°F, 65°C, 480°R but 300 K. Changes in temperature are indicated by putting the degree mark after the scale name: 25F°, 42C°, 800R° but 50 K.

THERMAL EXPANSIONS (SOLIDS)

The expansion of a rod, tape, rail, etc. depends on the original length, the material and the change in temperature.

$$\Delta L = \alpha L \Delta T \qquad 5$$

Where $\alpha$ is the coefficient of linear expansion. It is a property of matter (see table 2). Multiply by 5/9 to convert to 1/F°. Gaps are left in railroad rails and in the valve lift mechanism on an engine. Expansion joints are placed in concrete sidewalks and streets. Valve seat inserts can be installed by cooling them down and placing them in position. When thermal equilibrium is achieved, they will be set very tightly.

| Material | $\alpha$ (1/C°) |
|---|---|
| Aluminum | 0.000024 |
| Bronze | 0.000018 |
| Copper | 0.000017 |
| Iron | 0.000012 |
| Steel | 0.000011 |
| Flint glass | 0.000008 |
| Pyrex glass | 0.000003 |

Table 2. Coefficient of linear expansion

The circumference of a hoop or ring will increase when it is heated. This means the diameter also increases including that of the hole. A hole punched in a large plate will increase in size at the same rate as the plug that is punched out. As long as the plate and the plug are in thermal equilibrium, the plug will fit the hole. The diameter of the hole increases as the plate is heated.

A bimetalic strip is two lengths of metal fused together. When the temperature increases the strip will bend since one metal expands more than the other. This kind of expansion is called differential expansion. These are usually coiled and used in dial type thermometers or thermostats. The balance wheel of a watch is made of bimetalic materials.

AREA EXPANSION

When a square piece of sheet metal (length L and width L) is heated uniformly, it expands by $\Delta L$ in both directions. The original area is $L^2$ and the new area is $(L + \Delta L)^2$. If the expression for the new area is expanded it becomes:

$$(L + \Delta L)^2 = L^2 + 2L\Delta L + (\Delta L)^2 \qquad 6$$

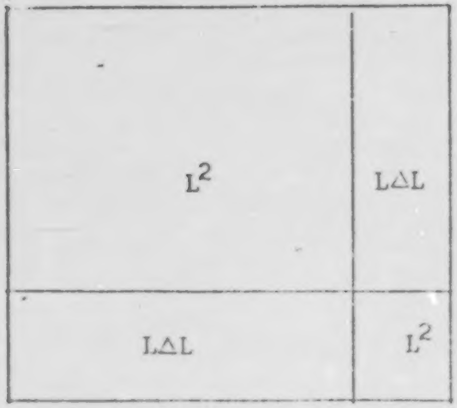


**Fig 1. Area expansion**

The terms of the expansion represent the areas shown in figure 1. If $\Delta L$ is small compared to L then $(\Delta L)^2$ will be a very small percentage of $2L\Delta L$ and can be ignored. If L is 10 cm, for example, the metal is steel and the temperature rise is 100°C, then $\Delta L$ equals 0.011 cm by equation 5. The middle term of equation 6 is 0.22 $cm^2$ and the last term is 0.000121 $cm^2$. The last term is only 0.055% of the middle term. So the middle term is considered as the entire increase in area If equation 5 is substituted for $\Delta L$ in the middle term, the change in area becomes:

$$\Delta A = 2\alpha A\Delta T \qquad 7$$

Where A is the original area.

## VOLUME EXPANSION

If a cube (length L on each side) is heated, it expands by $\Delta L$ on each side. The new volume becomes $(L + \Delta L)^3$. If this expression is expanded and the small terms dropped the change in volume is:

$$\Delta V = 3\alpha V\Delta T \qquad 8$$

Where V is the original volume. Notice that the volume coefficient for solids is three times the linear coefficient.

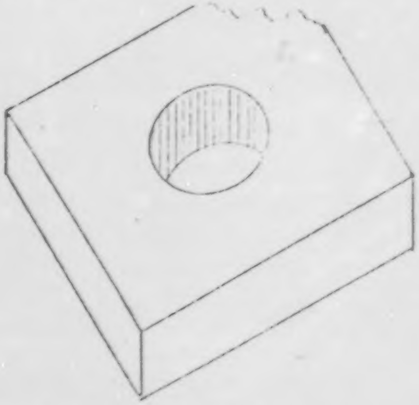


Fig 2. Expansion of a hole

A hole in a plate of metal expands both in diameter and thickness. If a thin sheet of metal was welded to the bottom, the hole would become a container. The change in volume of this little container can be calculated by using equation 8 if the temperature changes. The change in volume of the hole can be calculated just as if it were made of the same metal that surrounds it. The change in volume of any container (barrels, tanks, cans, bottles, etc.) can be obtained by using equation 8 and the correct coefficient of expansion.

## EXPANSION OF LIQUIDS

Liquids expand the same way solids do but there is no listing of linear coefficients for liquids. The volume coefficients have been determined for a number of liquids (see table 3). The formula for change in volume of liquids is:

$$\Delta V = \beta V \Delta T \qquad 9$$

Where $\beta$ takes the place of $3\alpha$ in equation 8. Do not multiply these numbers by 3.

Notice that the volume coefficients of expansion for liquids are all larger numbers than the volume coefficients for solids. Aluminum has a volume coefficient of $72 \times 10^{-6}/C^\circ$ while mercury has a coefficient of $180 \times 10^{-6}/C^\circ$. Any liquid will overflow its container when filled to the brim and allowed to warm up.

| Liquid | $\beta$ (1/C°) |
|---|---|
| Alcohol (methyl) | 0.00120 |
| Gasoline | 0.00105 |
| Mercury | 0.00018 |
| Water (20°) | 0.00037 |

Table 3. Volume coefficient of expansion

Example: A 100 gal steel tank is filled with 100 gal of gasoline. If the temperature increase in the afternoon is 25 C°, how much gasoline will overflow? NOTE: The differences in the expansion of the liquid and the tank determines the amount of overflow.

Given: $V = 100$ gal (tank and gasoline)
$\Delta T = 25\ C^\circ$
$\alpha = 11 \times 10^{-6}/C^\circ$ (steel)
$\beta = 105 \times 10^{-5}/C^\circ$ (gasoline)

Solution: $\Delta V = \beta V \Delta T$ (gasoline)
$= (105 \times 10^{-5}/C^\circ)(100 \text{ gal})(25\ C^\circ) = 2.63$ gal
$\Delta V = 3\alpha V \Delta T$ (steel tank)
$= 3(11 \times 10^{-6}/C^\circ)(100 \text{ gal})(25\ C^\circ) = 0.08$ gal
The overflow is 2.55 gal.

Example: By how much does the density of mercury change when the temperature increases by 100 C° if its original density at 0°C is 13.60 g/cm³. NOTE: The mass of a cubic centimeter will not change but its volume will.

Given: $d = 13.60 \text{ g/cm}^3$
$\Delta T = 100C^\circ$
$\beta = 18 \times 10^{-5}/C^\circ$
$V = 1 \text{ cm}^3$
$m = 13.6$ g

Solution: $\Delta V = \beta V \Delta T$
$= (18 \times 10^{-5}/C^0)(1 \text{ cm}^3)(100\ C^\circ) = 0.018 \text{ cm}^3$
New volume equals $1.018 \text{ cm}^3$
$d = m/v$
$= 13.60 \text{ g}/1.018 \text{ cm}^3$
$= 13.36 \text{ g/cm}^3$

Most materials expand when heated so the density decreases. Air rises when heated and sinks when cooled. Most fluids act the same way.

## WATER

There are a few materials that expand when cooled in certain temperature ranges and expand when heated at other temperatures. At temperatures above 4°C (40°F) water expands when heated. Below 4°C it expands when cooled. It expands also when it freezes. The less dense ice will flot on top of water. Water has its greatest density at 4°C.

## EXPANSION OF GASES

The expansion of gases is complicated by the fact that pressure, amount of gas and volume may change when the temperature changes. In the study of the kinetic theory of gases in module P 4 an equation for the average kinetic energy of the molecules was developed:

$$1/2m\overline{v^2} = 3/2kT$$

Where m is the mass of the molecules, $\overline{v^2}$ is the average square of their velocity, k is Boltzman's constant and T is the absolute temperature. If both sides of the equation are multiplied by the number of moles of gas (n) and Avagadro's number ($N_o$), the equation becomes:

$$1/2M\overline{v^2} = 3/2nRT \qquad 10$$

Where M is the total mass of the gas ($nN_om$) and R is the universal gas constant ($kN_o$).

When both sides of equation 10 are multiplied by two-thirds, both expressions are equal to the product of the pressure of the gas and its volume:

$$PV = 1/3nRT \qquad 11$$

This equation is known as the general gas law. If the n and T are transposed, the expression: PV/nT is seen to be a constant. Usually, the general gas law is written in this form:

$$\frac{P_1V_1}{n_1T_1} = \frac{P_2V_2}{n_2T_2} \qquad 12$$

Where subscript 1 denotes the initial conditions and subscript 2 indicates the conditions after a change has occured.

Equation 12 is usually written without the n's showing the relationship between pressure, volume and temperature when the amount of gas does not change:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad 13$$

In using this formula, remember to use absolute pressure and absolute temperature.

THERMODYNAMIC PROCESSES

Gases may undergo changes by five different "ideal" processes:

1. Isobaric process: An isobaric process takes place when a gas is heated in such a way that the pressure does not change. Water in a boiler of a steam engine, for example, is heated, vaporized and superheated all at a constant pressure. If the gas in a cylinder having a freely floating piston is heated, the temperature and volume increase without changes in pressure. Since $P_1$ and $P_2$ are equal in equation 13, they will drop out and the equation becomes:

   $$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad \text{(Isobaric)} \qquad 14$$

   This equation is known as Charles' law.

2. Isochoric process: An isochoric process takes place when a gas is heated at constant volume. The air or other gas in a sealed container undergoes an isochoric process when it is tossed into a trash fire. The pressure and temperature increase with practically no change in volume. It is an isochoric process up until the time the seam of the container splits and the can explodes (expands). Equation 13 becomes:

   $$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{(Isochoric)} \qquad 15$$

   It is known as Gay-Lussac's law.

3. Isothermal process: The temperature remains constant in an isothermal process. A slowly advancing piston in a cylinder will compress the air in the cylinder isothermally. Remember that an advancing piston speeds up the molecules (and therefore the temperature) so the process must take place slowly to allow heat to flow out of the system.

   $$P_1V_1 = P_2V_2 \quad \text{(Isothermal)} \qquad 16$$

   This equation is known as Boyle's law.

Notice that in the first three processes, heat must flow into the system or out of it. Heat is not allowed to flow in either direction in the next two processes.

4. Adiabatic process: When no heat enters or leaves a system, the process is said to be adiabatic. The compression stroke on a gasoline or diesel engine is approximately adiabatic since it occurs so quickly (at 3000 rpm, the compression stroke takes 1/200 s) that there isn't time for much heat to be transferred.

   The explosion of gasoline occurs so rapidly (before the piston starts downward), the explosion is approximately isochoric. After the explosion the expansion that occurs on the downward power stroke is again adiabatic. On a diesel engine, the power stroke is not adiabatic since burning occurs almost throughout the power stroke with a lot of heat being added. Equation 13 applies to this process:

   $$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad \text{(Adiabatic)} \qquad (13)$$ 17

5. Throttling process: When a fluid, originally at high pressure, passes through a narrow opening (such as a needle valve or an expansion valve) into a region of low pressure, the fluid undergoes an expansion known as the throttling process. In a mechanical refrigerator, fluid on the high pressure (and high temperature) side of the pump passes through the expansion valve as a continuous stream (liquid) into the low pressure side. There is no flow of heat between the high and low sides so the process is adiabatic. Formula 13 cannot be used since the liquid state is usually involved in the throttling process. The expansion is therefore much more complex involving changes in the internal energy of the fluid (attraction as well as kinetic).

Force is always present in thermodynamic process in the form of pressure. If motion takes place then, work will be accomplished. Note that work is done in all processes except isochoric. Changes in the internal energy of a gas occur in all processes in which a change in temperature occurs (all processes except isothermal). The flow of heat, changes in the internal energy and the work done in thermodynamic processes applied in the form of the law of conservation of energy forms the basis of the theory of heat engines and refrigeration devices.

Your textbook provides a number of example problems involving the gas laws.

PROBLEMS

## Module T 1 TEMPERATURE AND THERMAL EXPANSION

1. What is the freezing and boiling points of water at normal atmospheric pressure on the Celsius and Fahrenheit scales? How many degrees is there between each point on the two scales? One Fahrenheit degree is how many Celsius degrees?

2. What determines whether an object feels warm or cool to the touch? Explain the transfer of heat between an object's and your hand when the objects temperature is below 70°F, between 70°F and 98.6°F, at 98.6°F and above 98.6°F. When a book and a piece of metal are at 70°F, does one feel cooler than the other? Explain why?

3. When a mercury thermometer is placed in warm water, the mercury drops a little bit before rising. Explain why this happens. If it were placed in cold water would you expect it to rise a little before falling?

4. In the formula $\Delta L = \alpha L \Delta T$, does it matter whether the original or final length (L) is used?

5. What is an adiabatic process? If the ends of an unstretched rubber band are held with the center between your lips, then suddenly stretched, your lips will detect an increase in temperature. When the process is reversed, you will feel a decrease in temperature. Is this process adiabatic? Expain why the temperature of the rubber band changed.

6. Would you readily drink beer or a soft drink if its temperature was 277 K?

7. Would you willingly take a shower if the water temperature is 10°C?

8. During an illness, your temperature increased by 3.6 F°. Express this change on a Celsius thermometer.

9. Would you enjoy a pizza baked 20 min at 300°C and served with pepsi at 293 K?

10. Would you enjoy your favorite TV dinner if it had been baked for 30 min at 860 K and served with coke at 645°R?

11. The freezer compartment of a home refrigerator normally maintains a temperature of 0°F. At a temperature of 10°F or above, enzymes and other creepy-crawlies begin to cause food deterioration. If the actual temperature is 262 K, does the refrigerator likely need defrosting?

12. To conserve fuel, we have recently been asked to lower thermostats to 525°R. What is the recommended setting in in degrees Celsius?

13. If you wake up with a fever of 40°C, should you remain in bed?

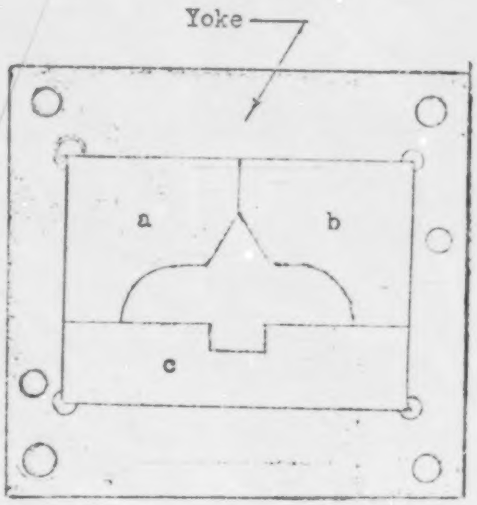
14. When heating a piece of iron, it will begin to glow red at about 1000°F (noticeable in the dark). Give the equivalent Celsius temperature.

15. Maximum oxyacetylene flame temperature is 6300°F. What is this temperature on the Celsius scale?

16. Aerosal spray cans of metal primer (paint) are not to be stored at a temperature above 130°F. Would a room where the temperature is never above 325 K be alright?

17. A plastic polyethylene lid for a metal can is formed in a mold at a temperature of 300°F. If the lid is to have a diameter of exactly 15 cm when it cools to room temperature (70°F), what is the diameter of the mold during the molding process? The coefficient of expansion of polyethylene is very high ($15 \times 10^{-5}/C^{\circ}$).

18. Steel die inserts are made in three pieces (a, b and c in the diagram) which when fitted together form a rectangle 2 x 3 in (exact dimensions) at 70 F. The steel yoke, when heated, will just fit over the inserts and when cooled should lock the inserts according to American Standard interference class force or shrink fit Fn2. This means the yoke must be made 0.0008 to 0.0027 in undersize for the 2 in dimension and 0.0010 to 0.0029 in undersize for the 3 in dimension. If the dimensions chosen are 0.0018 and 0.0027 undersize are chosen to what temperature would the yoke have to be heated to have internal dimensions equal to the die inserts? If the yoke is heated to 800°F for easy assembly, what will be its internal dimensions? The coefficient of expansion is $11 \times 10^{-6}/C^{\circ}$.



19. A micrometer is accurate if it and the object being measured are at 20°C (room temperature). The mike is made of steel with a linear coefficient of expansion of $11 \times 10^{-6}/C°$. It is used to measure a 4 in dimension on an aluminum workpiece. If the mike is at 15°C and the workpiece at 45°C, what is the error in the reading? If both are at 40°C? Aluminum has a coefficient of expansion of $24 \times 10^{-6}/C°$.

20. An inside mike has the same specifications as the one in problem 19, and is used to measure the 3 in inside dimensions of a die yoke (see problem 18). After milling, the yoke is at at temperature of 105°F and the mike is at 60°F What is the error in the reading? Both mike and yoke have a coefficient of expansion of $11 \times 10^{-6}/C°$.

21. A plastic 55 gal polyethylene drum is molded at 175°C. What is its internal volume if it must shrink to exactly 56.5 gal at 20°C (room temperature)? Polyethylene has a linear coefficient of expansion of $15 \times 10^{-5}/C°$.

22. The plastic 56.5 gal polyethylene drum in problem 21 is filled with 55 gal of ethylene glycol (antifreeze) at 50°F. If the temperature should rise to 120°F, will any of the ethylene glycol spill out the top? The volume coefficient of expansion of ethylene glycol is $30 \times 10^{-5}/C$ .

23. Air pumped into a tank has a temperature of 120°F and the compressor stops when a pressure of 150 $lb/in^2$ (gauge) is reached. If the volume of the tank doesn't change, what will be the gauge pressure in the tank after the air has cooled to 70°F? Assume the change is isochoric.

24. A large oxygen tank has 244 $ft^3$ of oxygen at atmospheric pressure and room temperature pumped into it. After the tank has cooled to room temperature, the gauge pressure is 2200 $lb/in^2$. What is the volume of the tank? Assume the compression is isothermal.

25. A small electric welder consists of a transformer in a metal housing. Considerable heat is produced by the transformer. Air comes in through an open screen in the bottom, is heated and then rises out the top through a louver. The air coming in the bottom is 20°C and the heated air is 50°C. The process is essentially isobaric since the housing is open to the outside. If the density of the air coming in is 0.0726 $lb/ft^3$, what is the density of the heated air?

26. The volume of a tire is 1500 $in^3$ and the gauge pressure is 30 $lb/in^2$. What volume will this air occupy at atmospheric pressure if the temperature doesn't change?

27. A truck tire has a gauge pressure of 90 lb/in$^2$ at a temperature of 60°F. After running at high speed on a hot afternoon the temperature increases to 140°F. If the change is isochoric, what is the gauge pressure?

28. A cylinder of an air compressor contains 11 in$^3$ of air at 13 lb/in$^2$ absolute pressure and a temperature of 80°F as it starts the compression stroke. At top dead center, the pressure has increased to 120 lb/in$^2$ (gauge) and the volume has decreased to 1.15 in$^3$ just as the exhaust valve opens. (The exhaust valve opens against pressure in the storage tank). What is the temperature of the compressed air?

## ANSWER KEY (PROBLEMS)

## Module T 1 TEMPERATURE AND THERMAL EXPANSION

1. 32°-212°F, 0°-100°C, 180F° and 100C°, 5/9
2. The rate at which heat flows from hand to object. The rate is normal at 70°F (room temperature). Below 70°F the rate of flow is faster than normal and the object feels cool or cold. Above 70 the rate of flow is less than normal and stops at 98.6°F. The object feels warm. Above 98.6°F the flow is from object to hand and the object feels warm to hot.
3. Glass bulb expands before heat gets to the mercury. Yes.
4. No.
5. A thermal expansion process during which time no heat is transferred into or out of the gas. Yes, approximately. Work is done on the rubber band. (Like bending a wire back and forth, it gets hot).
6. 40°F
7. 50°F
8. 2C°
9. 80.6°F-68°F
10. 1089°F-185°F
11. 12.2°F
12. 18.3°C
13. 104°F
14. 538°C
15. 3482°F
16. 126°F
17. 15.29 cm
18. 147°F, 2.016-3.024 in
19. 0.0026 in, 0.0010 in
20. 0.0039 in
21. 160.4 gal

22. Tank expands more than liquid, 0.99 gal (tank), 0.64 gal (liquid.

23. 136 lb/in$^2$

24. 1.62 ft$^3$

25. 0.0659 lb/ft$^3$ (1 ft$^3$ expands to 1.102 ft$^3$).

26. 4561 in$^3$ or 2.64 ft$^3$

27. 106 lb/in$^2$

28. 125°F

EXPERIMENTS

## Module T 1 TEMPERATURE AND THERMAL EXPANSION

PURPOSE: The purpose of this experiment is to study, by experimenting with one specific material, the expansion that occurs in solids when their temperature is increased.

CAUTIONS:

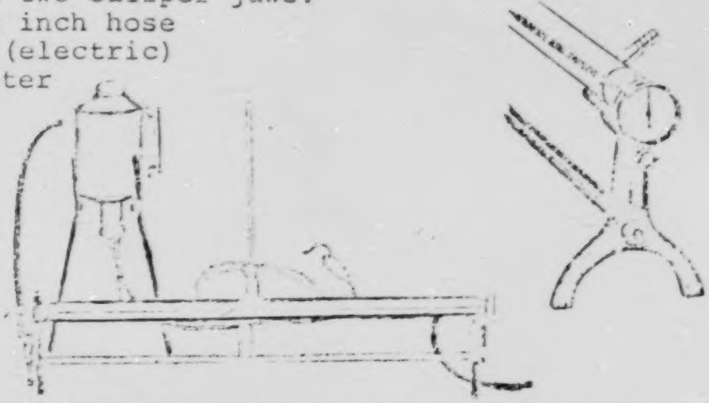
1. Read all the instructions before handling any of the pieces of equipment.
2. Never interfere with an experiment someone else is performing or with the equipment they are using. Horseplay is never appropriate in a laboratory situation.
3. Observe all cautions listed in the procedure section of these instructions.

EQUIPMENT: Check to see if all the following equipment is available before you start.

1. Linear expansion apparatus (Sargent-Welch #1633A)
2. Meter stick with two caliper jaws.
3. Two lengths of ¼ inch hose
4. Steam generator (electric)
5. Celsius thermometer
6. Beaker

INFORMATION: The change in length that occurs in a metal rod depends on the material, the change in temperature and the original length of the rod according to the following formula:

$$\Delta L = \alpha L \Delta T$$



By Permission: Sargent-Welch Scientific Co.

In this experiment you will measure the original length (L), the change in length ($\Delta L$) and the change in temperature ($\Delta T$) and calculate the coefficient of linear thermal expansion. You will then determine the material the rod is made of by comparing your calculated value with several values in a table.

PROCEDURE:

1. Fill the boiler two-thirds full of water, connect one hose to the boiler only. Put boiler on its stand and plug into the wall socket. Put the free end of the hose into the beaker and secure with a piece of tape across top of the beaker. While water is heating, proceed with steps three through fifteen.

CAUTION: Be careful not to upset the boiler. Do not touch heating coils or the boiler, accidently.

NOTE: When the boiler is plugged in it usually makes a noise. If it doesn't begin heating right away, have the instructor check it for you.

2. Hold the meter stick with the small numbers to the left. Assemble the caliper jaws onto the meter stick and set one on the 20 mm line exactly; tighten the clamp screw.

3. The tube of the linear expansion apparatus is supported at each end in "V's". At the front is a dial indicator that reads in millimeters (mm). At the other end is a positioning screw with locknut. Loosen the locknut and back-off the screw three or four turns.

4. Retract the pointer of the indicator with one hand and lift the end of the tube clear of the front "V". Release indicator pointer gently and remove tube from rear "V".

5. Place tube flat on the bench away from the edge. Do not drop!

6. The tube has a cork in each end that supports a metal rod. Check to be sure the rod ends extend out of the cork slightly.

7. Measure the length of the rod with the meter stick to the nearest one-half millimeter. Place the fixed caliper jaw against one rod end. Slide the second caliper jaw against the other rod end and tighten it. Be sure the meter stick is parallel to the tube. Record the length on the data sheet.

8. Remove meter stick from tube and read setting of both caliper jaws. Record both readings. Replace tube into the "V's" of the stand, starting with the end that goes under the hold down spring. Hold the pointer of the indicator retracted as the tube is placed in the front "V". Then release the indicator tip.

9. Wet the bulb end of thermometer with a drop of glycerin. Slide a short piece of rubber hose over the thermometer for safety. Gently push the stopper onto the bulb end of the thermometer, with a twisting motion. The bulb only should extend into the tube near the rod. NOTE: The thermometer bulb should not rest on the rod.

CAUTION: Use care when handling the thermometer. It is very fragile.

10. Slide the tube back until the end of the rod rests against the positioning screw. Turn the screw to move the tube toward the indicator until the indicator hand turns about one half turn. tighten the locknut.

11. Insert hoses on each end of the tube. The loose end of one should be placed in the beaker; the other (with metal tube connector) should lay loose on the table. DO NOT CONNECT TO THE BOILER.

12. Gently move indicator tip about a sixteenth of an inch from the rod end and release it. Do this two or three times until the indicator reading is constant.

13. Turn the outer rim of the indicator to position the zero exactly under the indicator hand. Do not bump or even touch the apparatus from this point on.

14. Read and record the temperature on the data sheet.

15. Steam should be emerging from the hose on the boiler by now. If it is remove it from the beaker and connect it to the hose with the metal hose connector on it.

NOTE: Quickly, check the indicator reading. It should still read zero.

CAUTION: From this point on the boiler, steam jacket and hoses will be hot.

16. When the thermometer reading is constant (near 100°C) for two or three minutes. Read the indicator to the nearest 0.005 millimeter. Record this reading and the final temperature on the data sheet.

17. Unplug boiler and let apparatus cool while the data is analysed.

18. Calculate the coefficient of linear thermal expansion for the rod.

19. Using the table below, identify the material the rod is made of from its coefficient of linear expansion.

### COEFFICIENT OF LINEAR EXPANSION

| Material | $\alpha$ (1/C°) |
|---|---|
| Aluminum | $24 \times 10^{-6}$ |
| Bronze | $18 \times 10^{-6}$ |
| Copper | $17 \times 10^{-6}$ |
| Iron (wrought) | $12 \times 10^{-6}$ |
| Steel | $11 \times 10^{-6}$ |

20. Dismantle equipment, empty water and return equipment to the drawer.

CAUTION: Be careful of hot boiler and hot water!!

# Applied Physics Module

SOUTHEAST COMMUNITY COLLEGE—Milford Campus
Milford, Nebr. 68405

Module: T 3

Title: TRANSFER OF HEAT

Module Contents:
1. Conditions for heat transfer
2. Conduction
3. Convection
4. Radiation
5. Law of cooling

Program: This module has been prepared expecially for students in:

1. Manufacturing Engineering Technology
2. Machine Tool and Design Technology
3. Welding Technology
4. Industrial Plastics Technology

Purpose: The purpose of this module is to study the transfer of heat energy. Heat is produced by friction in rotating equipment, in the cutting and grinding processes used in manufacturing, by combustion and the flow of electric currents. Heat must be removed in most cases for efficient operation. The subject of heat transfer is very important in manufacturing industries.

Producer: Gene Waring

Date Produced: March 1977

This project was performed pursuant to a grant from the State Board of Vocational Education through the Nebraska Research Coordinating Unit using federal funds made available under Public Law 90-576 part C, Research.

STUDENT INSTRUCTIONS

## Module T 3 TRANSFER OF HEAT

## OBJECTIVES

When you have satisfactorily completed this module, you will be able to:

1. Distinguish between temperature, heat and internal energy.
2. State the law that determines the direction of heat flow between two objects.
3. Describe each of the heat transfer processes: conduction, convection and radiation.
4. Understand that heat current is the rate of flow of heat and is expressed in units of power.
5. State the basic formulas for heat current (I) for each heat transfer process.
6. Solve various applied conduction, convection and radiation problems using the formulas in objective 5.
7. Describe the difference between good heat conductors and insulators and good radiators and poor radiators.
8. State Newton's law of cooling and solve various problems dealing with cooling.
9. Describe the nature of a heat sink and define such terms as: heat path, thermal connection, heat dam and temperature hill.
10. Describe the use of fins, fans, louvers, black paint, silver paint and a vacuum in heat transfer.

In order to satisfactorily complete this module, you must pass a test consisting of true-false, multiple choice, and problem type questions based on the objectives listed above with a grade of at least 80%.

## SELF-EVALUATION TEST

Perhaps you have had previous experience with the study of heat transfer. You may feel that your experience will enable you to perform most of the tasks listed in the objectives section above. A self-evaluation test (or sample test) is included in this booklet (pink paper) along with an answer key. You can evaluate your previous knowledge of the subject by taking this test (under normal test conditions) before you perform any of the learning activities listed below.

The result of this test is an indication of your knowledge. If you can answer all questions correctly, you may not need additional study. However, you should proceed with the learning activities if you can't answer all questions correctly. The answer key page (pink paper) directs you to various learning activities.

Before you take the instructor-graded test (post-test), read the "test" section at the end of these instruction pages (white paper).

LEARNING ACTIVITIES

The following list of activities is designed to help you achieve the objectives of this module. You are not required to complete all of the activities. They are intended to supplement your previous knowledge of the subject. If you wish, your instructor will recommend the learning activities you should complete.

I. Reading: The chapters, sections and page numbers are given for several textbooks. You may select your own textbook plus the information sheet that is included in this booklet. As you read, keep the list of objectives handy. Write down on separate paper a list of the definitions, laws, principles, formulas, etc., that the objectives refer to. This list will be very useful as an aid to memorizing them.

A. Information Sheet. Read the information sheets included in this booklet. They are printed on green paper. The information sheets cover subject matter that is presented only briefly or not at all in the textbooks.

B. Introductory Applied Physics, Harris, N.C., Hemmerling, E.M., McGraw-Hill, 3rd ed., 1972. Read all of chapter 15, pages 380-394 and chapter 16, section 16.3 pages 404-405.

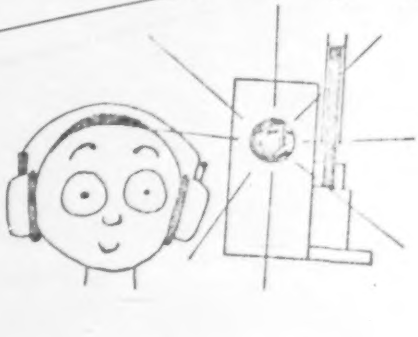
C. Elements of Physics, Smith, A.W., Cooper, J.N., McGraw-Hill, 8th ed., 1972. Read all of chapter 17, pages 222-231 and chapter 18, section 18.8, pages 241-242.

D. Physics for Career Education, Ewen, D., Nelson, R., Schurter, N., McFadden, L., Prentice-Hall Inc., 1st ed., 1974. Read chapter 16, section 16.4 pages 214-215 and Information Sheets (A).

E. Physics for Technology, Betts, J., Reston Publishing Co. Inc., 1st ed., 1976. Read chapter 15, sections 15.7, pages 251-257 and chapter 16, section 16.3, pages 270-271.

F. Modern Technical Physics, Beiser, A., Cummings Publishing Co. Inc., 1st ed., 1966. Read chapter 20, sections 20.1-20.3 and chapter 19, section 19.2, pages 297-298.

II. Listening/Viewing: The following single concept film loops (8 mm) are available in the Learning Resource Center (LRC). There is a brief training session given by the LRC staff to familiarize you with the film loop projector (Technicolor or Viewlex 702) and must precede the viewing of the films. Ask the LRC personnel about this training.



A. Convection In Liquids (BFA-Ealing 82-0050)

B. Temperature Waves (BFA-Ealing 80-2165)

C. Infra-Red Radiation (EBE S-81437)

D. Heat is Reflected and Absorbed (Doubleday 13115)

E. Heat Travels by Conduction, Convection and Radiation (Doubleday 13105)

F. Materials Conduct Heat at Different Rates (Doubleday 13125)

III. Solving Problems: Solve the problems in the problem set in this booklet. They are printed on ivory paper. Answers are given for each problem. Solve as many of them as you feel are necessary to gain competence in solving heat transfer problems. The problems from number five on are applied to your technology.

IV. Solving Problems (Optional): Solve some of the problems at the end of the reading set in your textbook. These are for additional practice if you feel it is needed and are mostly general interest problems.

V. Performing Laboratory Experiments: There is no experiment in this module.

TEST

You may proceed with the test at any stage of your study of this module; obtain a copy of the test, answer all questions, and return it to your instructor.

A grade of 80% is required for satisfactory completion of the module. A grade lower than 80% will require that you repeat the test. You must show evidence of further study before you repeat it, however. (Hand in your papers on problem solving, lab reports, etc.)

Every test you take on this module will be averaged to determine your module grade. Don't take the test until you have adequately prepared yourself to meet the requirements listed in the objectives section. Instead, go to the learning activities.

SELF-EVALUATION TEST

## Module T 3 TRANSFER OF HEAT

Read each question carefully and decide which one of the answers is best. Notice what letter your choice is. Then, on separate paper, write the problem number followed by the letter you chose. Take the test under normal test conditions; without help from other people and without references. The answer key is on the following page.

T - F 1. In order for heat to flow from one object to another, the two objects must contain different amounts of heat.

T - F 2. Conduction is the process in which heat energy is transferred from particle to particle without the actual transfer of material.

T - F 3. Natural convection involves the movement of a part of a liquid or gas which has a temperature that is different from the rest of the fluid.

T - F 4. Metals are better emitters of radiation than any other substance.

T - F 5. Newton's law of cooling applies to an object if the transfer of heat from it is by radiation only.

6. The materials with the highest coefficient of conduction are the:

   a) metals
   b) non-metal solids
   c) porous solids
   d) liquids

7. Which method of heat transfer is most involved when fans or pumps are used in industrial equipment such as a water pump on an automobile engine.

   a) Conduction
   b) Natural convection
   c) Forced convection
   d) Radiation

8. Find the total amount of heat energy in Btu that escapes through a window in one day if the heat current is 25 Btu/min.

   a) 600
   b) 1500
   c) 2 160 000
   d) 36 000

9. A solid concrete wall is 15 cm thick and has an area of 25 $m^2$. If the temperature difference averages 30 C°, find the heat current through the wall. (K = 0.0004 kcal/s m C°.)

10. An electric motor operates at a temperature of 55°C when used outdoors with an air temperature of -10°C. After being shut off, it cools to 50°C in 4 min. How much time is required for it to cool from 50°C to 45°C?

ANSWER KEY TO THE SELF-EVALUATION TEST

Module T 3 TRANSFER OF HEAT

| Question-Answer | | If you missed this question, you are directed to these learning activities |
|---|---|---|
| 1. | F | I Reading |
| 2. | T | I Reading or II Listening/Viewing |
| 3. | T | I Reading or II Listening/Viewing |
| 4. | F | I Reading or II Listening/Viewing |
| 5. | F | I Reading |
| 6. | a | I Reading or II Listening/Viewing |
| 7. | c | I Reading or II Listening/Viewing |
| 8. | d | III Solving problems |
| 9. | 2 kcal/s<br>120 kcal/min | III Solving problems |
| 10. | 5.26 min | III Solving problems |

INFORMATION SHEET

Module T 3 TRANSFER OF HEAT

Heat is produced whenever work is done against the force of sliding friction (in bushings or brakes, for example) or rolling friction (ball bearings), in the churning of turbulant fluid flow (automatic transmissions), in the elastic flexing or cutting of materials (tires, drill bits, etc.) and when electric current flows through a conductor (power resistors, diodes, transformers, etc. In most cases where energy is converted to heat by any of these methods, the heat is unwanted. The heat must be removed as it is produced or the objects' temperature will increase to a point where it operates inefficiently, is damaged or is destroyed.

Part of the heat that is produced on purpose by combustion of fuels (gasoline or diesel engines) or in nuclear reactions (power plants) is not utilized 100% and must be carried away. Even heat that is not produced by machinery and other equipment may be undesirable in certain places (food, living spaces) and must be removed by refrigeration.

In other cases, heat that is produced (on purpose or not) must be prevented from traveling along particular paths to critical areas or confined to a certain space. Heat diversions or heat dams may be used. A pair of pliers is used to hold a conductor while soldering connections. Most of the heat travels into the needle nose of the pliers instead of along the conductor where it could damage insulation and other electronic components. When copper pipe is being soldered with a torch, a wet rag will prevent excessive heat from reaching the wooden floor in a home.

When a torch is used to repair panels on an auto body an aqueous asbestos compound is used to create a heat dam to isolate the area being heated. This prevents buckling of the metal and protects rubber, glass, upholstery, paint, etc. The skirt of a piston must run cooler than the piston head to prevent excessive thermal expansion. A groove is cut around the piston above the top ring to reduce the cross section of the heat path. In addition a horizontal slot is cut below the bottom ring on both the front and back "sides". The piston head may operate at a temperature of 450°F while the entire skirt is less than 250°F. Insulation in a house is effective as a heat dam when recommended thicknesses are used.

The transfer of heat is an important subject. The following discussion gives more details about the processes involved and the conditions under which the transfer of heat will take place.

## HEAT AND INTERNAL ENERGY

The internal energy of a material is the total energy within it in the form of kinetic energy of the molecules and the potential energy of attraction between the molecules. Whenever two kinds of material are at the same temperature, the kinetic energy of the molecules is the same. The kinetic energy may be in the form of translational, rotational or vibratory motion. Light molecules move faster than heavier ones when their kinetic energy is the same.

Heat is energy which is in the process of being transferred from one object to another or from one part of an object to another as a result of temperature difference. It is incorrect to say that an object contains, possesses or has a lot of heat in it. It has internal energy within it. You may feel the heat being transferred from hot water to your hands when you plunge your hands into it. The internal energy of the hot water will be reduced and its temperature drops slightly as a result. You are not feeling the internal energy of the water. Instead you feel the heat being transferred to your hands.

If heat flows into or out of an object, its temperature changes unless freezing, melting, vaporizing or condensing is involved. Heat flow does not affect the temperature during a change of state. Once the transfer of heat is finished, the object will have undergone a change in its internal energy, either kinetic (temperature change) or attraction (change of state).

## THE SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics usually deals with the fact that although work can be completely converted to heat, heat cannot be completely converted into work. The kinetic energy of a car is completely converted to heat by the brakes and other frictional forces. The work done by a drill bit is all converted to heat. The energy used by a TV set is all converted to heat. The 2% or so converted to sound and light is absorbed by the air, walls and furniture in the room and changed to heat within seconds. However when heat is converted to work, only part is converted. Of all the heat produced by combustion in a gasoline engine, only about 30% actually does work on the pistons. The rest is dumped into the atmosphere by the exhaust or cooling system. A diesel engine will convert to work about 35% of the heat produced.

The greatest efficiency of any engine depends on the temperature difference between the hot cylinder and the cooler exhaust. Since the melting point and strength of metals determine the upper limit of high temperature and the atmosphere determines the lower limit for the cold, the efficiency never approaches 100%.

The internal energy of the atmosphere or the ocean is an enormous amount. It cannot be converted to work by any kind of engine, however, unless there is a colder reservoir into which some of the energy could be transferred. No process is possible in which the only result is the transfer of heat from a cold object to a warmer one. This statement is equivalent to the usual wording of the second law of thermodynamics. It is the relative temperature of two objects that determine the direction of heat flow in any natural process: always from hot to cold. The greater the temperature difference the greater the rate of flow.

The total amount of internal energy possessed by the two objects makes no difference. A lake of water frozen over in the winter time, for example, contains vastly more internal energy than a pot of boiling water. If the pot were submerged through a hole in the ice, heat would immediately be transferred from the pot to the lake until they came to thermal equilibrium.

Heat always flows from an object at a higher temperature to one at a lower temperature or from a region of higher temperature in a given body to a region that is cooler. The transfer of heat can occur by three different processes: conduction, convection and radiation.

HEAT TRANSFER

1. Conduction is the process in which energy is transferred from particle to particle without the actual transfer of material. Metals conduct heat with the help of freely moving electrons.
2. Natural convection is the movement of the material that contains the energy caused by the action of gravity (buoyancy) on the thermally expanded material (fluids).
3. Forced convection is the movement of the material containing the energy when the movement is forced by pumps, fans, etc.
4. Radiation is the movement of energy through space without the use of a carrier material. The energy consists of electromagnetic waves transmitted from an emitter to an absorber.

CONDUCTION:

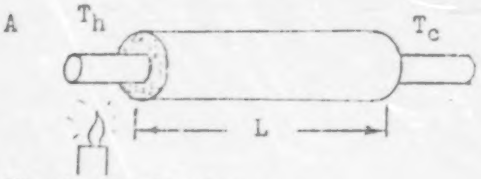


Fig 1 Conduction

If the end of a rod is heated as in figure 1, the hot molecules on that end will vibrate at a very rapid rate. They bump neighboring molecules and transfer energy in the process causing them to vibrate more rapidly, also. These molecules transfer energy to their neighbors by the same process and so on until the other end of the rod becomes warn. This is the process of conduction. Only the heat energy is transferred since the molecules can only vibrate in a fixed position.

Suppose the rod is insulated (see figure 1) and the heat flows in such a way as to maintain a fixed temperature difference $E = t_h - t_c$, where $t_h$ and $t_c$ are the hot and cold temperatures. The thermal resistance (R)is given by the formula $R = L/KA$ where K is the coefficient of conductivity of the material, A is the cross-sectional area and L is the distance the heat travels. The rate of flow or heat current (power) is given by $P = Q/t$ where Q is the amount of heat that flows in time t. The units of heat current are Btu/min, kcal/s, watts, etc. Heat current, rate of flow of heat, rate of heat transfer, power radiated, power dissipated, etc. are identical terms. Heat current is given by the formula:

$$P = \frac{E}{R} \qquad 1.$$

Notice this is the same as Ohm's law for the conduction of electricity except heat current has units of power which is not true of electrical current. It is for this reason that P is used for heat current instead of I. Other similarities between thermal and electrical conductivity are striking (see table 1).

| heat conduction | electrical conduction |
|---|---|
| Heat (Q) | Electric charge (Q) |
| Heat current $P = Q/t$ | Electric current $I = Q/t$ |
| Thermal resistance $R = L/KA$ | Electrical resistance $R = L/kA$ |
| Temperature differece $E = \Delta T$ (proportional to kinetic energy difference per molecule) | Potential difference E (electric energy difference between two points per coulomb of charge) |
| Relationship $E = PR$ | Relationship $E = IR$ |

Table 1 Comparison of heat and electrical conduction.

Heat current as expressed in equation 1 is usually given in textbooks in the following form:

$$P = Q/t = \frac{KA\Delta T}{L} \qquad 2.$$

Notice there will not be a heat current unless there is a temperature difference. Remember that heat flows from high temperature to low temperature. Table 2 lists the thermal coefficient of conductivities for various materials.

Table 2 Thermal coefficient of conduction.

| Material | | kcal/s m C° | Btu in/h ft² F° |
|---|---|---|---|
| Good | silver | 0.1 | 2880 |
| | copper | 0.09 | 2650 |
| | aluminum | 0.05 | 1460 |
| | iron-steel | 0.01 | 350 |
| | lead | 0.008 | 250 |
| Med | ice | 0.0005 | 15.6 |
| | sand | 0.0004 | 12.6 |
| | concrete | 0.0004 | 12.0 |
| | glass (plate) | 0.0002 | 5.5 |
| | water | 0.0001 | 4.3 |
| Poor | wood (varies) | 0.00003 | 0.80 |
| | vermiculite (loose) | 0.00002 | 0.46 |
| | rock wool | 0.00001 | 0.29 |
| | glass wool | 0.000009 | 0.26 |
| | styrofoam | 0.000009 | 0.25 |
| | air | 0.000005 | 0.17 |
| | vacuum | 0 | 0 |

Example: A 0.5 cm glass plate has an area of 3 m². The outdoor temperature is -20°C and indoor temperature is 22°C. (Surface temperatures must be used which are 18 C° (above outside) and 18 C° (below inside). Find the heat current, thermal resistance and total heat transferred in 12 hr.

Given:
$T_h = 2°C$
$T_C = -4°C$
$K = 0.0002$ kcal/s m C°
$L = 0.005$ m
$A = 3$ m
$t = 12$ h = 43 200 s

Solution: $P = \frac{KA\Delta t}{L}$

$$= (0.0002 \text{ kcal/s m C}^\circ)(3 \text{ m})(6 \text{ C}^\circ)/0.005 \text{ m}$$
$$= 0.72 \text{ kcal/s}$$
$$R = E/P = 6 \text{ C}^\circ/0.72 \text{ kcal/s} = 8.33 \text{ C}^\circ \text{ s/kcal}$$
$$\text{or } L/KA = 0.005 \text{ m}/(0.0002 \text{ kcal/s m C}^\circ)(3 \text{ m})$$
$$= 8.33 \text{ C}^\circ \text{ s/kcal}$$
$$Q = Pt = (0.72 \text{ kcal/s})(43\,200 \text{ s}) = 31\,000 \text{ kcal}$$

Convection:

Convection is the movement of heat by the actual transfer of the hot material (either liquid or gas). A qualitative description of the process is fairly simple. Air or other fluid near the heated object is warmed. It expands and becomes less dense. The buoyant effect on the hot, less dense fluid causes it to rise. Cooler fluid comes in from below and is heated in a continuous isobaric process and a convection current of fluid circulates in the near vicinity.

If the path of the convection current is obstructed, the flow will cease. If the object is producing heat continuously (such as a light bulb), it may overheat. The parts in a TV set would burn out quickly, if the screened bottom were covered.

Forced convection is produced when circulation is created by fans, pumps, etc. Even here, circulation must be unimpaired. An obstructed radiator on a car will soon cause the engine to overheat, for example.

If the inlet and outlet temperatures of a fluid carrying heat away from an object and the rate of flow, density and specific heat of the fluid are known, the amount of heat and the heat current being gained or lost by the fluid can easily be calculated. See the problem sets in module T 2 for several examples. However, the flow of heat away from a heated surface is very complex. Any subject involving fluid flow is complicated.

Heat current when the transfer is by convection of heat away from a hot surface is given by the formula:

$$P = hA(T_h - T_c) \qquad 3$$

Where h is the thermal coefficient of convection, A is the area of the surface (which can be increased by the use of fins, $T_c$ is the temperature of the heated surface and $T_h$ is the temperature of the fluid. The coefficient of convection is the complex part of the formula. It depends on the dimensions and orientation of the surface, difference in temperature between surface and fluid, acceleration of gravity and such fluid properties as the coefficient of viscosity, coefficient of conduction, specific heat at constant pressure, density and the volume coefficient of expansion. Formulas for horizontal, vertical and cylindrical surfaces have been derived and values of h have been determined. See A.L. King, Thermophysics, W.H. Freeman & Co., 1962 chapter 20 for further details.

RADIATION:

Energy is transported by radiation by means of electromagnetic waves. These waves do not require matter to be present as a transporting medium or carrier. In fact, matter such as air, glass, water, etc. that allows the passage of such waves, actually slows down the waves. In a vacuum, heat radiation travels at the speed of light ($3 \times 10^5$ km/s).

The heat current radiation from the surface of an object depends on the fourth power of the absolute temperature (Kelvin), the surface area (A), and the nature and color of the surface.

$$P = \alpha\sigma AT^4 \qquad 4$$

Where $\sigma$ is the Stefan - Boltzmann radiation constant ($5.67 \times 10^{-8}$ W/m$^2$K$^4$). This equation is known as the Stefan - Boltzmann law of radiation. The symbol $\alpha$ is the absorption factor. The absorption factor depends on the nature and color of the surface. See table 3. The letter A represents the total surface area of the heated object. Radiation can be increased by the use of fins on the object since this would increase the area of the surface.

| Material | $\alpha$ |
|---|---|
| Ideal black body | 1.00 |
| Lampblack | 0.95 |
| Black lacquer | 0.87 |
| Steel, oxidized | 0.79 |
| Copper, oxidized | 0.72 |
| Brass, oxidized | 0.60 |
| Tungsten | 0.35 |
| Copper, polished | 0.30 |
| Aluminum paint | 0.30 |
| Cast iron, bright | 0.22 |
| Aluminum, oxidized | 0.11 |
| Aluminum, polished | 0.04 |
| Silver, polished | 0.03 |
| Perfect mirror | 0.00 |

Table 3 Absorption Coefficient

Objects radiate heat according to equation 4. Objects that are good radiators or emitters of heat are also good absorbers of heat. If two objects have the same size, shape and temperature, they radiate or absorb heat according to their absorption coefficient. Black or dark surfaces radiate or absorb better than mirrors or light colored surfaces. See table 3. Lampblack (soot) approximates a perfect black surface while polished aluminum or silver surfaces approximates the perfect mirror. "Silvered" surfaces are used to prevent radiation from a vacuum bottle and some kinds of home insulation. Black paints are used on automobile radiators and electric motors to increase the radiation rates.

An object radiates heat and absorbs heat from its surroundings continuously. Both radiation and absorbtion are given by equation 4. The net rate of flow is given by: $P = \alpha\sigma A(T_0{}^4 - T_s{}^4)$ where $T_0$ is the temperature of the object and $T_s$ is the temperature of the surroundings. Notice that radiation would cease only if the temperature drops to absolute zero. Absorbtion would cease if all the surroundings were at absolute zero. The net rate of flow of heat is the difference between the heat radiated and that absorbed. If the object is hotter than the surroundings, it will lose heat. It will gain heat if it is cooler than the surroundings.

**Example:** A 5 cm steel ball (oxidized) is heated to 500°C. It is suspended in the center of a room at 20°C. What is the net rate at which heat is radiated from the ball? Do not include losses by conduction and convection.

Given:
$\alpha = 0.79$
$\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$
$T_h = 500°C = 773\ K$
$T_c = 20°C = 293\ K$
$d = 5\ cm = 0.05\ m$
$A = 4\pi r^2 = 4\pi(0.025\ m)^2 = 0.00785\ m^2$

Solution: Net rate = rate radiated - rate absorbed
rate radiated = $\alpha \sigma A T_h{}^4$:
$P = (0.79)(5.67 \times 10^{-8} W/m^2K^4)(0.00785\ m^2)(773\ K)^4$
$= 125.5\ W$
rate absorbed:
$P = (0.79)(5.67 \times 10^{-8} W/m^2K^4)(0.00785\ m^2)(293\ K)^4$
$= 0.5\ W$
net rate = 125 W = 0.03 kcal/s

A wide band of electromagnetic radiation is radiated by an object. At cool or cold temperatures the principal radiation is in the radio region (longer wavelengths). At hot temperatures the principal radiation is the shorter wavelengths of infrared radiation. At even higher temperatures the principal radiation shifts even more to shorter wavelengths (light and ultra-violet).

## NEWTON'S LAW OF COOLING

When conduction, convection and radiation are all involved in transferring heat from an object to its surroundings, the rate of transfer of heat (current) is approximately proportional to the difference in temperature between the object and its surroundings.

$$P = N(T_a - T_s) \qquad 5$$

Where N is a constant depending on the size and shape of the object. $T_a$ is the average temperature of the object and $T_s$ is the temperature of the surroundings. Equation 5 is called Newton's law of cooling and is approximately true provided the temperature difference is not too great.

Example: A house loses heat at a rate of 12 600 Btu/h, when the outside temperature is 20°F. Assuming the house is 65°F, how much heat would be lost per hour when the outside temperature is 0 F?

Given:
$T_h = 65°F$
$T_{c1} = 20°F$
$T_{c2} = 0°F$
$P_1 = 12\ 600\ Btu/h$

Solution: $N = P/(t_h - t_{c_1})$
$= (12\ 600\ \text{Btu/h})/(65°\text{F} - 20°\text{F})$
$= 315\ \text{Btu/h F}°$
$P = N(t_h - t_{c_2})$
$= (315\ \text{Btu/h F}°)(65°\text{F} - 0°\text{F})$
$= 20\ 500\ \text{Btu/h}$

Note that if N is multiplied by 24 h, it represents the Btu loss per degree-day for this particular house. If the outdoor temperature was above 65°F, flow would be into the house. However, the house temperature is usually taken to be 80°F to calculate cooling requirements. No heating or cooling is required between 65°F and 80°F (outdoor temperatures). The constant N is usually calculated by knowing the area, thickness, insulation, etc. of the walls, ceiling, floors, windows and doors. It can also be determined by using actual fuel usage and weather bureau data for the same period of time.

In the example above, the furnace maintained a constant temperature within the house. Heat losses change only if the outside temperature, winds, etc. change. In the case where no internal heat is produced, the temperature will drop if the temperature of the surroundings is lower than that of the object. Since $P = Q/t$ and $Q = mc\Delta T$ where c is the average specific heat of the object, equation 5 can be written (after substitution):

$$\Delta T = n(T_a - T_s)t \qquad 6$$

Where $\Delta T$ is the change in temperature, t is the time and n is a constant ($n = N/mc$).

Example: A cup of coffee cools from 180°F to 160°F in 2 min in a room where the temperature is 70°F. How much time would be required for it to cool from 120°F to 100°F?

Given: $\Delta T_1 = 20°\text{F}$
$T_{a1} = 170°\text{F}$
$T_{a2} = 110°\text{F}$
$T_s = 70°\text{F}$
$t_1 = 2\ \text{min}$
$\Delta T_2 = 20°\text{F}$

Solution: $n = \Delta T_1/(T_a - T_s)t$
$= 20°\text{F}/(170°\text{F} - 70°\text{F})(2\ \text{min})$
$= 0.1/\text{min}$
$t_2 = \Delta T/n(T_a - T_s)$
$= 20°\text{F}/(0.1/\text{min})(110°\text{F} - 70°\text{F})$
$= 5\ \text{min}$

Cooling proceeds rapidly when the temperature of the object is higher than that of the surroundings and much slower as its temperature approaches that of the surroundings. See figure 2. Temperature S is the temperature of the surroundings. Newton's law of cooling also applies to objects that are colder than the surroundings. In this case the object warms up instead of cooling. Remember that Newton's law of cooling only applies if the temperature difference is not too great.

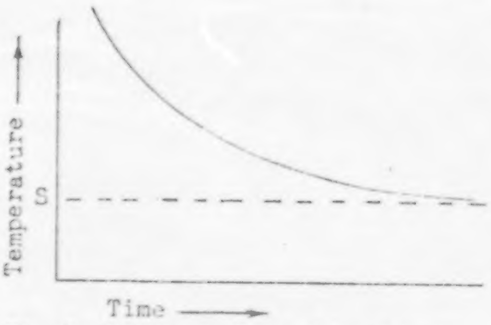


Fig 2 Newton's law of cooling

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REPORT

## Module T 3 TRANSFER OF HEAT

The following report should be completed by students in various technologies as required by the instructor.

Heat is produced whenever work is done against the force of friction, in the churning of turbulant flow, in the flexing, cutting or grinding of elastic materials, during combustion, by electric currents and by nuclear reactions.

I. Make a list of three (3) very specific examples of devices or equipment used in your technological field in which heat is produced by any of the methods described above. These should be devices or equipment in which the heat produced must be carried or transferred away to keep it working properly and efficiently. Give examples in which the heat transfer is accomplished mainly by conduction.

Conduction

A. Describe:

1. The device or equipment. Include a drawing or diagram of the device or paste in a picture from a magazine or newspaper.
2. How the heat is produced. Tell what parts are rubbing against each other or what parts have electric currents in them or what fuel is being burned, etc.
3. What would happen to the device if the heat is not transferred away.
4. The heat path along which the heat is conducted. Describe the material used for the heat path.
5. The heat sink to which the heat is transferred. NOTE: The heat sink may be an intermediate device such as a fin or other metal equipment. Do not trace the heat flow beyond this point even though the eventual heat sink may be air in a room, the atmosphere or outer-space.

II. Repeat part I, except describe examples (three) of equipment from which the heat is transferred mainly by convection.

III. Repeat part I, except describe examples (three) of equipment from which the heat is transferred mainly by radiation.

References and sources of information

1. Laboratory or shop equipment
2. Textbooks, shop manuals, etc.
3. Lab, shop and theory instructors are good sources of information

PROBLEMS

Module T 3 TRANSFER OF HEAT

1. What is the green-house effect. Explain why an automobile with closed windows gets much warmer inside than the outside air. How does a solar collector work?

2. Why should plates and cups with metalic or dark decorative markings not be used in a microwave oven?

3. Some objects you touch seem to feel cooler than others even though they are at the same temperature. (Touch the metal and wooden parts of your desk or table, for example). Explain why.

4. On a very cold day, a moistened finger will freeze to a piece of metal but not to a piece of wood. Explain why.

5. Each of the following statements are false. Explain why.

   a) Convection can take place only in gases.
   b) Heat transfer occurs between two bodies only when one is a better conductor than the other.
   c) At 100°C, a kilogram of water contains more internal energy than a pound of lead. If the lead was placed in the water, heat would immediately be transferred from the water to the lead.
   d) Black bodies are the best emitters of heat energy but silvered ones are the best absorbers. Hot air ducts and thermos bottles are silvered so heat is absorbed from the surroundings to keep the air or coffee hot, respectively.

6. Which of the following could be used for units of heat and which for units of heat currents? (a) joules, (b) horsepower, (c) calories, (d) Btu/h, (e) ft lb, (f) kcal/s, (g) kilowatt hour, (h) watts.

7. A heat-treating furnace has an internal temperature of 800°F. It is being used to expand the yoke to lock the die inserts with a shrink fit. The furnace is insulated with 5.5 in of high temperature insulating blocks which has a coefficient of conductivity of 0.82 Btu in/ft$^2$h F°. The door has an area of 95 in$^2$ and an outer temperature of 130°F. Find the heat current conducted through the door.

8. A heat-treating furnace has an internal temperature of 425°C and an outer surface temperature of 45°C. It has an average area of 1.4 m$^2$ for the heat path and a thickness of 13 cm of high temperature insulating blocks with a coefficient of conductivity of 0.00003 kcal/s m C°. Find the heat current conducted through the walls in kilocalories per second. How many watts is this?

9. The heat-treating furnace of the previous problem has an outer surface temperature of 45°C. The ambient temperature is 20°C.

Find the total heat current in watts being transferred to the air by convection. This must be calculated in two parts, then added (vertical and horizontal surfaces). The coefficient of convection for vertical surfaces is given by the formula: $h = 1.42(\Delta T/L)^{0.25}$ where L is the vertical height. The vertical height is 0.53 m and there is a total vertical surface area of 1.29 $m^2$. The coefficient of convection is given by the formula: $h = 1.93(\Delta T/L)^{0.25}$ where L is the characteristic horizontal dimension (0.65 m). The surface area is 0.49 $m^2$. About two-thirds of the heat coming from the horizontal surfaces comes from those facing upward. NOTE: $x^{0.25}$ means square root of the square root.

10. Calculate the net heat radiated from the surface of the furnace of the previous problem. The total surface area is 2.27 $m^2$. Assume the surface temperature is a uniform 45°C. The absorption coefficient is 0.92 (black paint). The ambient temperature is 20°C.

11. Combine the answers to problems 9 and 10 and compare with the answer to problem 8. Should the heat transferred to the air by convection and radiation from the surface be equal to the heat conducted to the surface from inside? If the heating coils (electric) in the furnace are rated at 6.5 kW, what fraction of the time is the thermostat on?

12. What is a heat exchanger? Exactly what do they do? Give four examples of where they might be used in which the transfer of heat is from 1. gas to gas, 2. gas to liquid, 3. liquid to gas and 4. liquid to liquid.

13. A deep cut is made on the workpiece on a lathe. Cutting oil is used as a coolant which flows at a rate of 450 mℓ/min. The temperature of the oil flowing onto the workpiece is 24°C and 38.5°C when it runs off. If the specific heat and density of the oil are 0.43 kcal/kg C° and 890 $kg/m^3$, respectively, find the rate at which heat is absorbed by the oil in kilocalories per minute and in watts.

NOTE: Heat is produced in hydraulic circuits within the pump, hydraulic motors, relief valves, flow control valves, pressure reducing valves and in the plumbing. This heat must be removed to prevent the build-up of corrosion, sludge and varnish and to prevent the oil from thinning with loss of lubricating ability. Heat is transferred to the surrounding air by radiation and convection from the various parts listed above as well as the reservoir. Modern oils allow temperatures of 80°C to 85°C and heat exchanger should be used if the temperature exceeds 70°C.

14. After several hours of operation it is found that the surface temperature of the reservoir and other parts of a hydraulic circuit is 95°C in an ambient temperature of 25°C. The rate of heat loss from the system by convection and radiation (see Newton's law of cooling) is 1.05 kcal/s. What would be the heat current from the same surfaces if a heat exchanger (cooler) is installed so the surface temperature is 60°C?

15. In the previous problem, what is the rate at which heat is removed by the heat exchanger? Express your answer in kilocalories per second, kilowatts, Btu per hour and horsepower.

16. If the hydraulic circuit in problem 14 is shut off, the reservoir cools from 60°C to 55°C in 11 min. How much time is required for it to cool from 50°C to 45°C? From 40°C to 35°C? The ambient temperature is 25°C.

17. If the hydraulic circuit in problem 14 was used outdoors in the summer time at a temperature of 35°C, what would be the temperature of the reservoir and other parts without the heat exchanger? What effect would there be on the operating temperature if the sun was shining directly on the reservoir?

18. Why is the angle of the cutting edge on drill bits or other cutting tools important. How is the heat transfer by conduction away from the cutting edge affected when the angle is made too small? How does this affect the temperature of the cutting edge?

19. Match each numbered word with a lettered word: A radiation, B conduction, C insulation, D convection.

1. Fin
2. Fan
3. Black paint
4. Silvered surface
5. Silver metal
6. Vacuum
7. Copper
8. Styrofoam
9. Solid
10. Liquid
11. Gas
12. Metal

ANSWER KEY (PROBLEMS)

Module T 3 TRANSFER OF HEAT

1. Radiation from the sun is transmitted through glass, plastic etc. It is absorbed by objects inside greenhouse, car, solar collector, etc. It reradiates as a longer wavelength of radiation which is not transmitted by the glass. Thus the internal temperature increases.

2. They absorb more radiation than the rest of the container. Temperature increases with accompanying differential expansion and breakage.

3. Heat is conducted away, rapidly by metals so heat flow continues from your hand giving the sensation of coolness. Heat piles up on surface of non-conductor so heat transfer decreases.

4. See question 3.

5. a) Liquids to but not solids
   b) Only when there is a temperature difference
   c) At the same temperature there would be no heat transfer.
   d) Black bodies are good emmitters and good absorbers. Silvering is used to prevent radiation losses.

6. Heat: a,c,e,g. Heat current: b,d,f,h.

7. 65.9 Btu/h

8. 0.12 kcal/s, 514 W

9. 173 W

10. 337 W

11. 510 W, yes, 7.8%

12. A device which conducts heat through a thin metal wall from one flui to another. 1 Refrigerator condenser or gas furnace, 2. Hot water heater, 3. Car radiator, 4. Water cooled oil on hydraulic pumps, dynamometers,etc.

13. 2.5 kcal/min, 174 W

14. 0.57 kcal/s

15. 0.48 kcal/s, 2.01 kW, 6860 Btu/h, 2.69 hp

16. 15.9 min, 28.6 min

17. 105°C, higher

18. If angle is correct, large mass of steel is near cutting edge where heat is produced and provides a larger area for the heat path.

Decreases. Increases. ($Q = mc\Delta T$: If Q remains the same but m decreases then $\Delta T$ must increase).

19. A: 1,3,4
B: 5,7,9,12
C: 6,8
D: 1,2,10,11